

Excess capacity and the race to fish: the role of capital malleability, environmental variation and quota management

Steven Rust, B.Ec (Hons.)

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Statement of Co-Authorship

The following people and institutions contributed to the publication of work undertaken as part of this thesis:

Steven Rust (Tasmanian School of Business and Economics) = Candidate

Dr. Satoshi Yamazaki (Tasmanian School of Business and Economics) = Author 1

Dr. Sarah Jennings (Tasmanian School of Business and Economics) = Author 2

Author details and their roles:

Paper 1, Excess capacity and capital malleability in the fishery with myopic expectations

Located in chapter 2; Candidate (80%), Author 1 (10%), Author 2 (10%).

Candidate was the primary author, with both Author 1 and Author 2 contributing to the interpretation of results and the development of the manuscript.

We the undersigned agree with the above stated “proportion of work undertaken” for each of the above published (or submitted) peer-reviewed manuscripts contributing to this thesis:

Signed:

Dr. Satoshi Yamazaki

Supervisor

Tasmanian School of Business

and Economics

University of Tasmania

Dr. David Adams

Head of School

Tasmanian School of Business

and Economics

University of Tasmania

Date: 30 November 2015

Abstract

Excess capacity is a major issue in world fisheries. In addition to reducing the ability of managers to control the global harvest and increasing the potential for effort spill-over between fisheries, excess capacity introduces a prospective level of economic waste in the fishery. When there is excess capacity in a fishery, more inputs are being used than is necessary to produce the current output and economic theory suggests that the net benefit to society from the resource exploitation is not maximised. Fishery managers worldwide are concerned with reducing the levels of excess capacity in their fisheries. In fisheries where ‘race to fish’ behaviour is prominent, competitive harvesting can also encourage inefficient investments in capital which create the potential for problematic excess capacity. Such behaviour is termed the ‘race to invest’ in this thesis.

The objective of the thesis is to investigate how race to fish and race to invest behaviours affect the level of excess capacity. The thesis consists of three essays, in which excess capacity is examined in the open access fishery, where the race to fish and race to invest are pervasive, and also during a period of race behaviour in a catch-controlled fishery. The first essay investigates the relationship between the malleability of capital and the level of excess capacity using a dynamic model of the open access fishery. The malleability of capital in this essay is represented by a difference between the purchase and resale prices of capital. The second essay investigates the connection between environmental variation and excess capacity, also in the open access fishery. This essay characterises the emergence of excess capacity under transient fluctuations in recruitment, and also uses parameterised simulations to investigate excess capacity when there is a regular cyclical fluctuation in recruitment and for ‘positive’ and ‘negative’ regime shifts, where the recruitment of the fishery permanently

increases or decreases. In these essays, the race to fish and the race to invest are modelled separately, so the conventional race to fish determines the level of fishing effort (i.e. capacity utilisation) and the level of capital investment is driven by a race to invest, in which fishers' expectations are formed myopically (according to the theory of projection bias). The third essay undertakes an empirical analysis of excess capacity and efficiency in the Tasmanian rock lobster fishery using the Data Envelopment Analysis methodology. This essay investigates whether the adjustment of the fishery, after the introduction of the Individual Transferable Quota (ITQ) system in 1998, has occurred over a prolonged period of time. This would suggest that the ITQ system may have a larger impact on excess capacity in that fishery than is indicated by comparable studies in other fisheries. In addition, this essay looks for evidence of the re-emergence of excess capacity in the fishery during a period of non-binding Total Allowable Catch (TAC) between the 2008 and the 2010 quota years.

The results in this thesis highlight a potential trade-off between excess capacity and the biological outcome for the fishery, which suggests caution in using the level of excess capacity as an indication of the fishery's health. The results also show that the reduction or elimination of excess capacity can be achieved through increasing the malleability of capital or by the cessation of competitive investment during transient positive fluctuations in recruitment. Finally, the thesis finds little evidence for a temporal change in either excess capacity or efficiency following the introduction of an ITQ system in the Tasmanian rock lobster fishery, and confirms that a period of non-binding TAC in that fishery was not associated with an increase in excess capacity.

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Chapter 1. Introduction

1.1 Background

Marine fish production is an important source of protein and supports the livelihoods of many people worldwide (Coulthard et al., 2011, Badjeck et al., 2010, Pollnac and Poggie, 2006).

According to the 2014 State of World Fisheries and Aquaculture report, the proportion of marine fish stocks harvested within biologically sustainable levels declined from 90.0 percent to 71.2 percent between 1974 and 2011 (FAO, 2014). Almost one third, i.e. 28.2 percent, of fish stocks were estimated to be overfished at the end of 2011. Despite the steady decline in fish production since the mid-1990's, the number of vessels and fishers has continued to increase worldwide (FAO, 2014). The world population of fishers was in the order of 39.4 million people in 2012, and has increased by around 4.1 percent per decade since 1990 (FAO, 2014). In a 2009 report entitled *The Sunken Billions: The Economic Justification for Fisheries Reform*, the FAO and the World Bank jointly estimated that the lost economic benefit from global marine fisheries due to overfishing was in the order of US\$50 billion per year, and pointed to excess capacity as a major contributor.

Excess capacity occurs when more inputs are being used than is necessary to produce the given output, and consequently the net benefit to society from the resource exploitation is not maximised (Pascoe et al., 2003). In an optimally controlled, i.e. sole-owner, context such excess capacity reflects the profit-optimal decisions of the fisher (Poudel et al., 2013, Ward et al., 2005). Because prices and the biomass of the fishery fluctuate over time it may be beneficial to keep a higher capability to catch fish than is needed for most of the time, i.e. in order to take higher catches when economic or environmental conditions allow. However, in

situations where the fishery's management is sub-optimal, so that behaviours associated with unregulated or pure open access fishing persist, it cannot be assumed that excess capacity represents the culmination of economically efficient decisions. Such excess capacity can reduce the ability of managers to effectively regulate catch and effort (Gréboval and Munro, 1999), and when it is addressed by the reallocation of capital to other fisheries, may lead to the spill-over of fishing pressure between fisheries (Bockstael and Opaluch, 1983, Munro and Clark, 2003). Improving our understanding of the relationship between excess capacity and its drivers is important to the development of policies that can better avoid economic waste and inefficient harvesting in world fisheries.

The literature identifies the concept of capital malleability, which describes the ease with which the capital stock can be adjusted, as being of central importance to the problem of excess capacity (Gréboval and Munro, 1999, Clark and Munro, 2002). When capital is not perfectly malleable, meaning that it cannot be immediately and costlessly adjusted either up or down by fishers, capital may be retained in the fishery that would otherwise be disposed of in order to achieve a given level of fishing effort. The literature also identifies a link between environmental variation and excess capacity in fisheries (Ward et al., 2005, Poudel et al., 2013, Ludwig et al., 1993). In the pure open access fishery, Ludwig et al. (1993) describe the relationship between fluctuations in the abundance of fish and excess capacity. In a process, termed 'Ludwig's ratchet', episodes of favourable recruitment improve the short run profitability of the fishery, and encourage fishers to increase fishing capacity.

This thesis makes a contribution to our understanding of the roles of both the malleability of capital and environmental variation in explaining the emergence and persistence of excess capacity in fisheries where harvesters exhibit racing behaviour; that is where incentives

encourage wasteful competitive harvesting and investment. While there is a vast amount of literature regarding fishing capacity (Pascoe et al., 2003, Pascoe, 2007, Kirkley et al., 2002, Kirkley and Squires, 1999, Pomeroy, 2012) and on racing behaviours in fisheries (Townsend, 1990, Feeny et al., 1996, Branch et al., 2006, Weninger and McConnell, 2000), very little work has focused specifically on the nexus between such behaviour and excess capacity. Furthermore, where such work exists in the literature it has not explicitly captured the development of excess capacity as an endogenous process fuelled by racing behaviour and affected by capital malleability and environmental variation.

1.2 The race to fish and the race to invest

Where resources are non-excludable and rivalrous in consumption, any more than a small number of harvesters will typically engage in a cycle of competitive overuse and overinvestment that culminates in resource degradation. This problem is well understood in fisheries (Gordon, 1954, Schaefer, 1957), where a lack of property rights or effective regulation, coupled with the possibility for prodigious gains, gives rise to competitive behaviours that are associated with overharvesting and resource depletion. This race to fish is typically accompanied by a race to invest, in which fishers accumulate fishing capacity in their competition for harvest (Weninger and McConnell, 2000, Branch et al., 2006, Munro and Clark, 2003, Gréboval and Munro, 1999). Depending upon the circumstances of the fishery, the margins over which capital is accumulated and rents dissipated include both the number of vessels in the fishery and the level of capitalisation of fishing activity, as fishers make inefficient use of inputs in their competition for harvest.

Such racing behaviours are particularly evident in unregulated, or pure, open access fisheries (Madau et al., 2009, Salayo et al., 2008, Teh and Sumaila, 2007). However, even in cases where fishers and fish stocks are subject to regulations that are imperfect or ineffectively enforced, behaviours and outcomes may resemble those characteristic of open access. For example, in fisheries regulated by input controls, such as a season length restriction or limited entry licencing, the development of excess capacity is well understood (Munro and Clark, 2003, Townsend, 1990). Under limited entry, excess capacity has long been known to result from ‘capital stuffing’ (Townsend, 1985), where the competition for harvest encourages fishers to gradually accumulate better gear, larger vessels, and other technology improvements over time. In fisheries regulated by a season length restriction, excess capacity has been demonstrated in connection with the competition for harvest and reductions in season length by the fishery’s manager (Munro, 2010, Munro and Clark, 2003, Gréboval and Munro, 1999). Even in catch controlled, ITQ managed fisheries, racing behaviour has been observed when the total allowable catch (TAC) does not bind the total harvest. In such circumstances, the fishery effectively reverts to a limited entry, regulated open access paradigm (Emery et al., 2014, Kompas et al., 2009, Grafton et al., 2007, Kompas and Gooday, 2007). Such fisheries also experience racing behaviour when fish populations are heterogeneous, so that some areas are more productive than others, and also when there are more favourable times to harvest during the fishing season (Costello and Deacon, 2007).

Racing behaviour in open access fisheries is associated with the near sightedness, or myopia, of fishers’ behaviour. In traditional static equilibrium models of open access (Gordon, 1954), vessels continue to enter the fishery, so long as harvesters perceive a positive return from doing so. However, as rational profit seekers, fishers ignore the negative externalities, and

hence underestimate the cost their decisions impose on others as they either drawdown the fish stock or contribute to congestion among vessels, until all rents are dissipated through over-harvesting and over-investing. Dynamic bioeconomic models of open access which focus on the transition pathway of the fishery to equilibrium have also generally assumed that myopic harvesters enter the fishery in direct proportion to the current profit of the fishery, and not on forecast or projected profits (Smith, 1968, Smith, 1969, Bjørndal and Conrad, 1987). In this myopic model, fishers effectively apply very high discount rates to future events so that only the present conditions are relevant for their decision making. Later work applied the idea of rational expectations in fisheries where fishers have perfect foresight about future conditions of the fishery (Berck and Perloff, 1984), and this has since been applied in a number of studies (McKelvey, 1985, Clark et al., 2005, Eisenack et al., 2006).

Although there is a growing body of empirical literature examining different forms of expectations and decision making in fisheries (Teh et al., 2014, Johnson and Saunders, 2014, Feeny et al., 1996), the definitive nature of expectations in the fishery remains unclear. One such model of myopic expectations, and the one adopted for the theoretical modelling in this thesis, is ‘projection bias’, in which fishers interpret themselves in the future as being the same as themselves in the present, so that they place an overemphasis on the present conditions in decision making (Loewenstein et al., 2003, Loewenstein, 2000). Examples of this have been found in catalogue orders (Conlin et al., 2007), the volatility of equity prices (Mehra and Sah, 2002) and in the car and housing markets (Busse et al., 2012); and the importance of projection bias has also been investigated in medical decision making (Loewenstein, 2005). In the fisheries literature, Berck and Perloff (1984) applied this form of myopic expectations in their model of an open access fishery.

1.3 Fishing capacity and excess capacity

Despite the importance of excess capacity to effective fisheries management, and the large amount of research that has been done in this area, both theoretically (Clark and Munro, 2002, Gréboval and Munro, 1999, Munro and Clark, 2003, Poudel et al., 2013, Ward et al., 2005) and empirically (Dupont et al., 2002, Kirkley et al., 2002, Vestergaard et al., 2003, Squires et al., 2010, Solís et al., 2014b), much terminology is still variously defined and is used inconsistently in many cases. The concepts of capacity and excess capacity in fisheries are difficult to both define and understand (Pascoe et al., 2003).

The literature is dominated by three concepts of fishing capacity, and these are: ‘engineering’, ‘economic’ and ‘technical’ capacity. Engineering capacity refers to the maximum power output (i.e. wattage) of equipment in the fishery (Pascoe et al., 2003, Berndt and Morrison, 1981, Klein, 1960). This definition is widely regarded as being too simplistic for a meaningful economic analysis of fisheries, since it does not account for the behavioural characteristics of the fishery, i.e. the way fishers use their fishing equipment (Coelli et al., 2001, Klein et al., 1973). By contrast, economic capacity explicitly accounts for optimising behaviour among fishers, and measures capacity in terms of some optimum value such as minimum cost or maximum revenue (Kirkley and Squires, 1999, Pascoe et al., 2003). Klein (1960), for example, defines economic capacity as occurring at the minimum of the short run average cost curve. When there are long run constant returns to scale, Berndt and Morrison (1981) note that this point also will be at a tangency of the short and long run average cost curves. More recent definitions include Coelli et al. (2001), Fousekis and Stefanou (1996) and Fagnart et al. (1999), who define economic capacity as the profit maximising level of output. In general, however, the lack of cost data in fisheries precludes the use of economic measures of capacity (Pascoe et al., 2003). Exceptions are, for example, Pascoe and Tingley

(2006) who use a non-parametric ray approach to estimate economic capacity, and also Lindebo et al. (2007) who estimate revenue-based capacity utilisation measures for the Danish North Sea trawl fleet.

For this reason, fishing capacity is most often defined following a technical definition, where the fishing capacity is defined based on the maximum physical output of a fleet or vessel under normal or customary operating conditions (Pascoe et al., 2003, Johansen, 1968, Färe et al., 1989), and the modelling works in this thesis (Chapters 2 and 3) have adopted the technical definition of capacity.

In fisheries economics literature, the maximum output attainable under normal operating conditions is referred to as fishing capacity¹ and the capacity utilisation ratio is defined as the ratio of observed output to the fishing capacity, given the current biomass and conditions in the fishery (Pascoe et al., 2003, Kirkley et al., 2002, Gréboval and Munro, 1999, Kirkley and Squires, 2003). Using the technical definition of fishing capacity, excess capacity is said to exist when the capacity utilisation ratio is less than one, i.e. fishing capacity remains underutilised in the fishery. Excess capacity is therefore defined without reference to the optimum or target level of fishing capacity, as being any situation where the capacity utilisation ratio is less than one (Pascoe et al., 2003, Kirkley et al., 2002, Gréboval and Munro, 1999). This is in contrast to overcapacity, which is defined based on the economic measure of capacity, and represents the difference between the observed and target levels of production in the fishery. The conventional technical definition of fishing capacity does not account for the optimising behaviour of fishers.

¹ The terms ‘capacity,’ ‘fishing capacity,’ and ‘capacity output’ have been used interchangeably in this thesis.

A variant of technical capacity that is commonly applied in empirical studies, and is used in the empirical work in this thesis (Chapter 4), is referred to as ‘technological economic’ capacity. This definition was suggested by Färe et al. (2000), and later Kirkley et al. (2002), and measures fishing capacity as the maximum observed, instead of the maximum physical, output for a given set of physical, environmental and economic conditions. By measuring capacity output directly from observed production data, the technological economic definition accounts for optimising behaviour to the extent that such behaviour is encapsulated in the measurements of an economic dataset.

1.4 Thesis aims and structure

The overarching objective of this thesis is to investigate the link between the racing behaviour of fishers and excess capacity. This is done within the open access fishery, where both race to fish and race to invest behaviours are prevalent, and also where race behaviour re-emerges in a managed fishery. Within the context of race behaviour, the role of two key factors known to influence the extent to which capital is accumulated and excess capacity occurs are explored. They are the malleability of capital and environmental variation. In both cases our interest is in how these factors interact with race behaviour to create excess capacity that persists in the long run equilibrium of the fishery and is not of a purely transitory nature. The thesis addresses these aims in three essays.

The first essay (Chapter 2) focuses on the relationship between the malleability of capital and the emergent level of excess capacity in fisheries where the race to fish and the race to invest are prominent. Using a dynamic model of the open access fishery, this essay examines the connection between the range of steady state levels of excess capacity and the degree of

capital malleability. In a parameterised simulation of this model, the relationship between steady state excess capacity and the initial values of biomass and capital is investigated; as well as the importance of key economic and biological parameters (i.e. the price of fish, the fishers' discount rate, the environmental carrying capacity and the intrinsic growth rate) in determining the level of excess capacity.

The second essay (Chapter 3) investigates the link between environmental variation and excess capacity. Using an adaptation of the traditional Gordon-Schaefer model, this essay analytically investigates the emergence of excess capacity under transient increases or decreases in recruitment. In a parameterisation of the model, this essay further investigates levels of excess capacity for regular cyclical fluctuations in recruitment and also in the case of 'positive' and 'negative' regime shifts, i.e. permanent increases and decreases in recruitment respectively.

The models developed in both the first and second essays are novel in that they separate, analytically, the race to fish and race to invest behaviours, and thereby account for the endogenous emergence of excess capacity in the fishery. A common link between the first and second essays is also the modelling of fishers' near sighted behaviour, which is captured in both essays according to the theory of 'projection bias' (Loewenstein et al., 2003, Loewenstein, 2000). However, the two essays contrast in their respective representations of capital malleability. In the first essay, capital malleability is represented by the difference between the purchase and resale prices of capital; and in the second essay it is modelled using the rate of capital depreciation, with higher rates denoting greater malleability. Both specifications are consistent with the models of such malleability proposed by Clark et al. (1979), and capture the ease with which capital can be retired from the fishery. In the case of

the first essay, capital malleability directly captures the cost of exiting the fishery by accounting for the difference between the purchase and resale price of capital. In general, the malleability of capital increases with the availability of alternative uses of the fishing capital and the ease of transitioning between different fisheries or fish stocks (i.e. the transferability of fishing rights, the universality of fishing equipment, and the geographic distance between fish stocks).

The third essay (Chapter 4) presents an empirical analysis of excess capacity in the Tasmanian rock lobster fishery, which has been managed through an Individual Transferable Quota (ITQ) system since 1998. The essay uses the Data Envelopment Analysis methodology to estimate levels of efficiency and unbiased capacity utilisation from a census of log book data for the fishery from the 2000 to the 2013 quota years. Using these measures, the third essay investigates the change in excess capacity in the fishery during a period following the introduction of the ITQ system, intended to reduce or eliminate race behaviours, and over a period of non-binding TAC in the fishery, when race behaviour has been observed to re-emerge.

A final chapter concludes the thesis and suggests areas for future research.

Chapter 2. Excess Capacity and Capital

Malleability in the Fishery with Myopic

Expectations

This essay has been accepted for publication in Marine Resource Economics.

2.1 Introduction

Fishing capacity has long been recognised as a major obstacle to the conservation and long term sustainable use of marine resources (Crutchfield, 1956, Gulland and Robinson, 1973, Clark, 1977). In 1999, the Food and Agriculture Organization of the United Nations (FAO) committed to an International Plan of Action for the Management of Fisheries Capacity (FAO, 1999). This plan called for FAO member nations to take immediate measures to monitor and address the level of capacity in their fisheries. Nevertheless, capacity remains a significant issue in world fisheries, and the goals of preventing the emergence of new, and of managing existing, capacity remain high on the policy agendas of fishing nations worldwide (FAO, 2008, OECD, 2009, Pomeroy, 2012, Salomon and Holm - Müller, 2013).

The emergence of excessive fishing capacity is widely associated with situations where the ‘common-pool’ characteristics of the fishery result in a race to fish and invest (Clark and Munro, 2002, Munro, 2010). While such behaviour can persist in a regulated fishery (Homans and Wilen, 1997) and under a range of property institutions, including rights-based regimes (Costello and Deacon, 2007, Asche et al., 2008, Emery et al., 2014), the twin

problems of race to fish and race to invest behaviour are most pervasive in a fishery where access is unrestricted and fishing regulations are ineffective¹. In the fisheries literature, overcapacity and excess capacity are defined as separate concepts and treated as different issues. Overcapacity is generally defined as the difference between the current and the target level of production in the fishery. The concept of overcapacity can be thus used as an indicator of long term excessive fishing capacity and used to indicate how much capacity needs to be adjusted in the fishery (Pascoe et al., 2003). Excess capacity, on the other hand, is defined as the difference between the current production level and the maximum potential production of the fishery for a given level of inputs under normal operating conditions.² Excess capacity is thus often portrayed as a temporary feature of the fishery, such as when fish stocks vary over time and the level of potential catch is different for different stock sizes (Pascoe et al., 2003).

Central to the problems of excess and overcapacity is the concept of malleable fleet capital (Gréboval and Munro, 1999, Munro, 2010), which describes the ease with which capital may be bought and sold. If capital is perfectly malleable, fishing capital can be bought and sold at no cost, so that there will be no excess and overcapacity in the fishery (Gréboval and Munro, 1999). When this is not the case, the costliness of adjusting the capital stock will mean that fishing capital could be retained in the fishery that would otherwise have been disposed of in

¹ This is not to say that excess capacity does not exist in regulated, restricted access fisheries.

² It is important to note that various definitions of excess capacity and overcapacity have been proposed and discussed in the literature (Gréboval and Munro, 1999, Clark and Munro, 2002, Pascoe et al., 2003, Ward et al., 2005). In addition, the terms excess capacity, overcapacity and overcapitalisation are often used interchangeably.

order to achieve the desired level of fishing effort. This additional capital, whether it continues to operate in the fishery or remains idle, contributes to excess and overcapacity. The resulting economic waste emerges from the fact that the existing level of fishing capacity, such as the number of vessels, exceeds its 'optimal' or 'target' level and from the existence of underutilised capacity, which is a product of the vessels which are not engaged or not 'fully' engaged in fishing (Gréboval and Munro, 1999).

Our main aim in this essay is to develop a stylised model to explore the relationship between the malleability of capital and the emergent level of underutilised capacity, referred to here as excess capacity, in the case of a fishery where fishers engage in both a race to fish and invest. Although operating the fishery with some underutilised capacity may be desirable when the harvesting and investment behaviours are both optimally controlled (Poudel et al., 2013), the process whereby capital accumulates and excess capacity emerges in the presence of the race to fish and invest behaviours is not well understood in the literature. In addition to the generation of pure economic waste in the form of underutilised fishing capacity excess capacity results in reduced ability of fisheries managers to effectively regulate effort and catch. Furthermore, where the problem of excessive fishing pressure in one fishery is addressed by reallocating underutilised capacity to other fisheries, excess fishing pressure may spill-over between fisheries (Bockstael and Opaluch, 1983, Munro and Clark, 2003). Understanding the drivers of excess capacity is therefore important for policy makers in developing measures that will result in improved management of marine resources by avoiding the problems of overharvesting and economic waste frequently associated with excessive fishing capacity (Munro and Clark, 2003, Pascoe, 2007).

There are a number of studies exploring issues of optimal fisheries management when capital adjustment is either not possible or costly (Clark et al., 1979, Charles and Munro, 1985, Boyce, 1995, Singh et al., 2006, Poudel et al., 2013). To the best of our knowledge, there are only a small number of existing models of the fishery in which incentives to race to fish and invest are represented and capital adjustment is assumed to be costly (McKelvey, 1985, Munro and Clark, 2003, Eisenack et al., 2006). The previous studies, however, assume that the existing capacity is either fully utilised or not utilised at all by the fishers who exploit the fishery and are therefore unable to account for the extent of excess capacity. As far as we are aware, our model is the first to incorporate both purchase and resale prices for capital, and to specify an endogenous level of capacity utilisation in the fishery where fishers engage in both a race to fish and race to invest.

We develop a dynamic model of a fishery with quasi-malleable capital, in which there is no constraint on investment, but such adjustment is costly because underutilised capacity can be sold only at a price lower than its purchase price (Clark et al., 1979). The model incorporates race to fish behaviour based on the assumptions of the conventional open access fishery model (Smith, 1969, Bjørndal and Conrad, 1987). We adopt the investment rule described by McKelvey (1985), in which the capital stock is adjusted such that the average return to current capital is equalised to the average cost of investing, thereby representing the race to invest. Consistent with the traditional portrayal of fishers' behaviour in the open access fishery as a race to fish based on observed current profits (Smith, 1969, Bjørndal and Conrad, 1987) and with empirical evidence (Feeny et al., 1996, Teh et al., 2014), our model assumes that fishers form expectations on the returns to capital with reference to current conditions in the fishery only. This form of myopic behaviour is known as projection bias in the

behavioural economics literature (Loewenstein, 2000, Frederick et al., 2002, Loewenstein et al., 2003).

The contributions of this essay are twofold. First, we analytically characterise the evolution of the capital stock and the fish stock with quasi-malleable capital and show that multiple equilibria with varying levels of excess capacity exist due to the different purchase and resale prices of capital. Second, using a parameterised version of our model, we show how the initial conditions of the fishery, that is the initial levels of the biomass and capital stock, influence the steady state level of excess capacity that will emerge in the fishery where a race to fish and invest is pervasive. We further explore the sensitivity of this relationship for various biological and economic parameters.

2.2 The model

2.2.1 Fishing effort and capital

In the conventional bioeconomic model of the fishery, fishing effort represents an aggregate measure of the levels of all inputs, such as time, capital, labour and fishing gear. Following Clark et al. (1979), however, we separate capital from other inputs involved in fishing and assume that the level of fishing effort, E , is constrained by the capital stock, K , measured in standardised vessel units, such that $0 \leq E \leq K$. We further assume that $E = \phi K$, such that $\phi \in [0, 1]$ is the capacity utilisation ratio which measures the proportion of the current capital stock effectively engaged in harvesting. Our specification of ϕ in this way is consistent with

the technical definition of capacity (Kirkley and Squires, 1999, Pascoe et al., 2003).³ Using this definition, capacity utilisation in this essay is measured as the ratio of the production of the fishery to the maximum potential production for a given level of inputs, under normal operating conditions.

2.2.2 Harvest function and biomass dynamics

For the harvest and effort relationship, we use the Schaefer production function (Schaefer, 1957) given as:

$$h = qx E = qx \phi K \quad (2.1)$$

where h is harvest, q is the catchability coefficient and x is the total biomass of the fish stock.

The biomass dynamics are:

³ An alternative definition of capacity is the ‘economic’ definition, which attempts to account for an optimum level of output in terms of the economic parameters of the fishery. Klein (1960) and Berndt and Morrison (1981) develop such a concept based on short run and long run average cost curves. Fagnart et al. (1999) and Coelli et al. (2001) propose definitions centered on a profit-maximising level of output, while others define capacity in terms of the firm’s cost and revenue functions (Färe et al., 2000). In most fisheries, however, the general lack of cost data often precludes the use of economic measures (Pascoe et al., 2003). A variant of this definition, known as technological-economic capacity is commonly used in the empirical literature to measure capacity in fisheries (Dupont et al., 2002, Kirkley et al., 2002, Squires et al., 2010).

$$\dot{x} = G(x) - qx\phi K \quad (2.2)$$

where $G(x)$ is the natural growth of the population and we use the density-dependent logistic growth function $G(x) = rx(1 - x/\bar{x})$, where r is the intrinsic growth of the fish species and \bar{x} is the environmental carrying capacity.

2.2.3 Fishery profit and malleability of capital

The economic profit of the fishery accounts for the cost and benefit of investment in addition to the net revenue generated from fishing (Clark et al., 1979), such that:

$$\pi = ph - cE - c_f(I) \quad (2.3)$$

where p is the unit price of landed fish, c is the cost per unit of fishing effort and I is the level of investment. The cost of investment, $c_f(I)$, for the two cases of investment ($I > 0$) and disinvestment ($I < 0$) in the capital stock is given as:

$$c_f(I) = \begin{cases} c_I I & \text{if } I > 0 \\ c_S I & \text{if } I < 0 \end{cases} \quad (2.4)$$

where c_I and c_S are the purchase and resale price of capital, such that $c_I > c_S > 0$.

Clark et al. (1979) characterise the level of malleability of capital in terms of investment, I , and the purchase and resale price of capital, c_I and c_S , and the rate of depreciation on capital, γ .⁴ In the general case of quasi-malleable capital in which there is a secondhand market for capital ($c_S > 0$), there is no constraint on investment ($-\infty < I < \infty$), but such adjustment is costly because the capital cannot be sold in the secondhand market at its purchase price ($c_I > c_S$). We represent the relationship between the purchase and resale prices of quasi-malleable capital in terms of two key parameters: the depreciation rate of the capital stock, γ , and the rate of time discount rate, δ , as:⁵

⁴ When capital is perfectly non-malleable, investment is irreversible. Disinvestment or resale of capital is not possible ($I \geq 0$ and $c_S = 0$) and the depreciation on existing capital is zero ($\gamma = 0$). By contrast, when capital is perfectly malleable, investment is immediately reversible so that capital can be disinvested at its purchase price. There is no constraint on investment ($-\infty < I < \infty$) and the purchase and resale prices of capital are assumed equal ($c_I = c_S$).

⁵ From Equation (2.4), replacing the depreciation on a single vessel, i.e. $I = \gamma \cdot (1) = \gamma$, costs $c_I I = c_I \gamma$ at an instant of time. Using the standard cost of capital for the fishery, i.e. $\gamma + \delta$ (Clark et al., 1979), the present value of this cost over the duration of a vessel's life can be given as $c_s = \int_0^\infty \gamma c_I \cdot e^{-(\gamma+\delta)\tau} d\tau$. Solving this equation gives $c_s = \gamma c_I / (\gamma + \delta)$, which is Equation (2.5). This identity will hold in a competitive market because, if the scrap vessel is more expensive than c_s , the owner will prefer to source replacement parts from a wholesaler or the vessel's manufacturer. Whereas if the scrap vessel is less expensive than c_s , the scrap capital will become the owner's preferred source of parts. In this case, the demand for scrap vessels will increase, which will push up their price, and this should continue until scrap vessels are no longer less expensive than the replacement parts

$$c_s = \frac{\gamma c_I}{\gamma + \delta} \quad (2.5)$$

The level of capital malleability, therefore, decreases as the time discount rate increases, reflecting the fact that the resale price of capital, c_s , in a competitive market will fall as the present value of the stream of services is expected to yield declines. Similarly, with Equation (2.5), capital is assumed to be more malleable at higher rates of capital depreciation, which effectively result in a shorter period of time being needed for a given capital stock to be reduced by the non-replacement of depreciated capital. In this essay we are interested in the case of quasi-malleable capital, where $c_I > c_s > 0$, and thus we assume that the discount rate δ and the depreciation rate γ are positive. Equation (2.5) can also be written as a ratio of the resale price of capital to the purchase price of capital, so that $c_s/c_I = \gamma/(\gamma + \delta) < 1$. We use this ratio as a measure of capital malleability, such that the closer the ratio is to one, the easier it is to adjust capital in the fishery and hence the greater the malleability of capital.

from a wholesaler or the manufacturer. The value $c_s = \int_0^\infty \gamma c_I e^{-(\gamma+\delta)\tau} d\tau$ therefore represents the price a vessel owner will ultimately be prepared to pay for a scrap fishing vessel.

2.2.4 Net investment

In a fishery involving a race to invest, positive economic profits attract new fishing operators that represent additional capital stock in the fishery. This continues until all economic returns from capital investment have been dissipated. We capture this capital accumulation process in our model by assuming the capital stock in the fishery continues to grow ($\dot{K} > 0$) so long as capital in the fishery earns a positive economic profit, or specifically so long as the average return to current capital ($\bar{\mu}$) is greater than the purchase price of capital ($\bar{\mu} > c_I$).

Likewise, we assume that capital is removed from the fishery ($\dot{K} < 0$) when the average return to current capital is below the resale price ($\bar{\mu} < c_S$), since in this case fishers will profit from disinvesting the underutilised capital. Finally, we assume that fishers will have no incentive to adjust the capital stock ($\dot{K} = 0$) when the average return to current capital is between the purchase and resale prices ($c_S < \bar{\mu} < c_I$). Given this investment behaviour, the evolution of the capital stock can be written as:

$$\dot{K} = \left(\frac{\bar{\mu}}{c_f} - 1 \right) K \quad \text{or} \quad \dot{K} = \begin{cases} (\bar{\mu}/c_I - 1)K & \bar{\mu} > c_I \\ 0 & \text{if } c_I \geq \bar{\mu} \geq c_S \\ (\bar{\mu}/c_S - 1)K & \bar{\mu} < c_S \end{cases} \quad (2.6)$$

where the term $(\bar{\mu}/c_f - 1)$ indexes the relative size of the average return on investment to its price in the fishery. Using Equation (2.6) together with the capital dynamics equation

$\dot{K} = I - \gamma K$, we derive the investment rule as:

$$I = \left(\frac{\bar{\mu}}{c_f} - 1 \right) K + \gamma K \quad (2.7)$$

Following McKelvey (1985) we specify the expected current value of the average return on investment at time t as:

$$\bar{\mu}(t) = \int_t^{\infty} \max \left[pqx^e(\tau) - c, 0 \right] e^{-(\gamma+\delta)(\tau-t)} d\tau \quad (2.8)$$

where $\max[.]$ is the max operator and $x^e(\tau)$ is the expected level of biomass for the future period $\tau > t$. Given that the values of $x^e(\tau)$ are not realised at time t for all $\tau > t$, the average return on investment at time t depends on the expectation of the future biomass level. In our model we adopt a form of myopic behaviour known as projection bias, where individuals systematically interpret themselves in the future as being similar to how they are in the present, and therefore place an over-emphasis on current conditions when making decisions (Loewenstein, 2000, Loewenstein et al., 2003). Examples of projection bias have been established in the behavioural economics literature (Frederick et al., 2002, Mehra and Sah, 2002, Loewenstein, 2005, Busse et al., 2012) and Berck and Perloff (1984) also use this form of myopic expectations in their model of an open access fishery. Projection bias contrasts with the traditional model of myopia (Smith, 1969, Bjørndal and Conrad, 1987) in

which fishers apply extremely high discount rates to future events (Johnson and Saunders, 2014, Teh et al., 2014) so that only the present conditions determine their behaviour.

Assuming that in their race to invest, where fishers' expectations of future conditions are formed myopically, future biomass is expected to be the same as current biomass, (i.e., $x^e(\tau) = x(t)$ for all $\tau > t$), the average return to current capital given in Equation (2.8) can be re-written as:⁶

$$\bar{\mu}(t) = \int_t^{\infty} (pqx(t) - c) e^{-(\gamma + \delta)(\tau - t)} d\tau \quad (2.9)$$

Integration of Equation (2.9) yields:

$$\bar{\mu}(t) = [pqx(t) - c] / (\gamma + \delta) \quad (2.10)^7$$

⁶ The $\max[.]$ operator no longer appears in this expression since the fishery would not shutdown in advance of the realization of negative net harvest revenue under the assumption of myopic expectations.

⁷ Unlike McKelvey (1985), the average return on investment at time t in our model does not follow a dynamic specification. The dynamic specified by McKelvey relies on the assumption of perfect foresight and disappears when we adopt projection bias.

Equation (2.10) represents the average return on investment at time t in the fishery with myopic expectations of future biomass.

2.2.5 Capacity utilisation ratio and excess capacity

In the presence of race to fish behaviour, fishing effort increases so long as the economic profit from the fishery is positive (Smith, 1969, Bjørndal and Conrad, 1987). We capture this process in our model through the adjustment in the capacity utilisation ratio, ϕ , which we assume occurs instantaneously and thus $\phi = c_f(I)/(pqxK - cK)$ from Equations (2.1) and (2.3). Using this capacity utilisation ratio and the investment rule in Equation (2.7), the proportion of current capital engaged in fishing can be derived as:

$$\phi = \begin{cases} \frac{1}{\gamma + \delta} - \frac{(1-\gamma)c_I}{pqx - c} & \text{if } \bar{\mu} > c_I \\ \frac{\gamma c_I}{pqx - c} & \text{if } c_I \geq \bar{\mu} \geq c_s \\ \frac{1}{\gamma + \delta} - \frac{(1-\gamma)c_s}{pqx - c} & \text{if } \bar{\mu} < c_s \end{cases} \quad (2.11)$$

where the capacity utilisation ratio is bounded between zero and one.

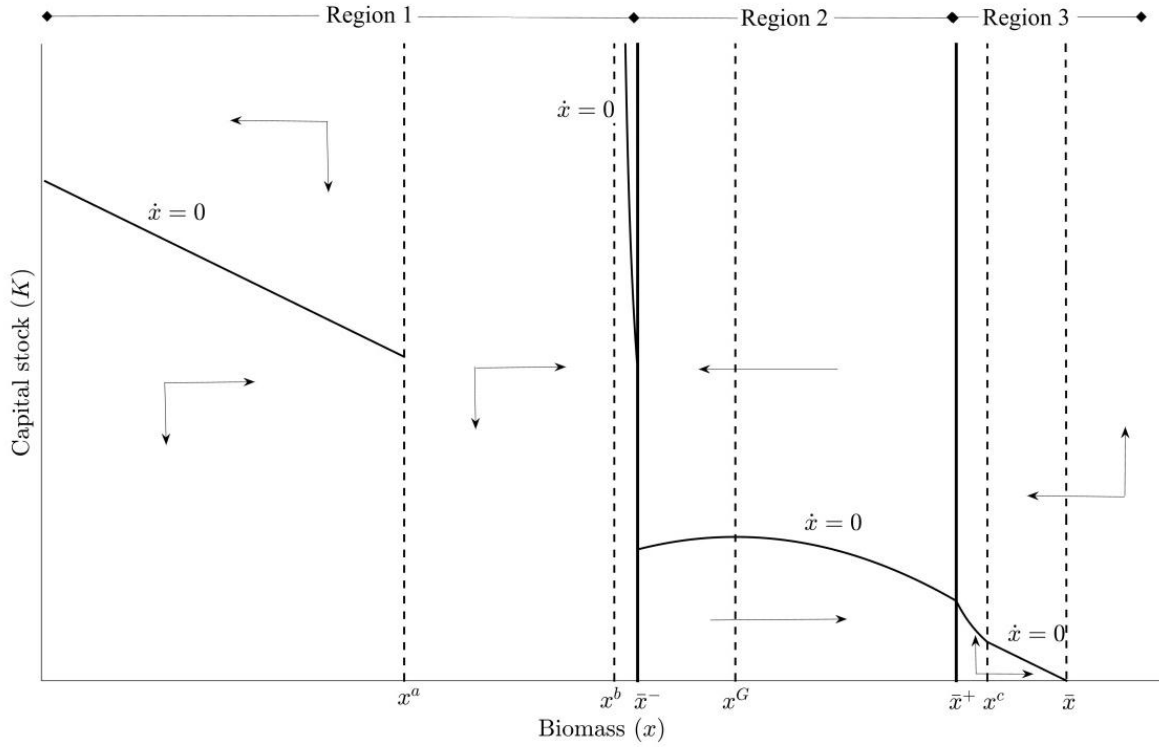
The capacity utilisation ratio in Equation (2.11) represents the level of underutilised capacity in the fishery. In this essay, we use ϕ to index the level of excess capacity as $\Phi = 1 - \phi$ where Φ takes a value between zero and one. For example, $\Phi = 0$ implies that the fishery operates at full capacity, and hence $h/h_c = 1$ where h_c is the maximum harvest level attainable in the

fishery for a given capital stock (i.e., capacity output). In contrast, when $0 < \Phi \leq 1$, the actual level of harvest is less than the full capacity output, such that $h/h_C < 1$, and therefore excess capacity exists in the fishery. Given Equation (2.11), the level of capacity utilisation, ϕ , and hence excess capacity, $\Phi = 1 - \phi$, in the fishery is uniquely determined for a given level of the biomass, x , the catchability coefficient, q , and the economic parameter values of the fishery.

2.2.6 The dynamics of a fishery with quasi-malleable capital

Figure 2.1 presents a capital-biomass phase portrait showing the dynamics of the capital stock, K , and biomass, x , in a fishery with quasi-malleable capital. The evolution of the capital stock is defined by three regions, denoted as Region 1, Region 2 and Region 3. The boundaries between the regions are defined by the solid vertical lines at $x = \bar{x}^-$ and $x = \bar{x}^+$ where $\bar{x}^- = [(\gamma + \delta)c_S + c]/(pq)$ and $\bar{x}^+ = [(\gamma + \delta)c_I + c]/(pq)$. In Region 1, the capital stock in the fishery decreases because the average return to current capital is below the resale price of capital ($\bar{\mu} < c_S$) prompting disinvestment. By contrast, the capital stock increases in Region 3 because the average return on investment is greater than the purchase price ($\bar{\mu} > c_I$). In Region 2, the average return to current capital is between the purchase and resale price ($c_S \leq \bar{\mu} \leq c_I$) and the capital stock is stable.

Figure 2.1: Phase portrait: capital and biomass dynamics with quasi-malleable capital.



Using Equation (2.11), we identify ranges of the biomass associated with corner solutions where the current capital stock is either fully utilised ($\phi = 1$) or not utilised at all ($\phi = 0$). In Region 1, when the biomass is between $x^a = c/(pq)$ and $x^b = [(1-\gamma)(\gamma+\delta)c_s + c]/(pq)$, no capital is utilised. In Region 3, the current capital is fully utilised when the biomass is greater than $x^c = [(1-\gamma)(\gamma+\delta)c_t + (1-\gamma-\delta)c]/[pq(1-\gamma-\delta)]$. For all other areas of the phase plane, the capacity utilisation ratio is between zero and one ($0 < \phi < 1$). From an examination of x^a , x^b , x^c , \bar{x}^- and \bar{x}^+ it can be shown that, for all parameterisations of the model, the following holds true:

$$0 \leq x^a < x^b < \bar{x}^- < \bar{x}^+ < x^c < \bar{x} \quad (2.12)$$

The evolution of biomass is determined by the biomass nullcline which is the set of curves marked as $\dot{x} = 0$ in Figure 2.1. The biomass nullcline represents the combinations of capital and biomass for which the fish stock is constant over time, such that:

$$\dot{x} = 0 \quad \Leftrightarrow \quad K = \frac{rx(1 - x/\bar{x})}{qx\phi} \quad (2.13)$$

Using Equations (2.11) and (2.13), we derive the full specifications of the biomass nullcline for all levels of biomass as summarised in Table 2.1. The dynamics of the fishery with quasi-malleable capital in our model are characterised by this biomass nullcline and the dynamics of the capital stock as discussed above. For instance, in Region 3 where the capital stock in the fishery increases over time, the biomass increases when the level of capital is below the biomass nullcline. This situation reflects a fishery where the level of exploitable biomass is high, but the number of existing vessels exploiting the fish stocks is small and, in turn, the biomass increases. Conversely, the biomass decreases in the same region when the capital is above the nullcline because the number of vessels exploiting the fish stock is high and fishing pressure on the fish stocks is correspondingly relatively high. In Region 1, when the biomass is below the traditional bionomic equilibrium, x^a , the average return to current capital given in Equation (2.10) is negative and this leads to an immediate disinvestment of existing capital

to the level where there is no capital stock in the fishery and therefore the fishery is economically collapsed. By contrast, in the same region but when the biomass is above the traditional bionomic equilibrium, the average return to current capital is positive and therefore the economic collapse of the fishery does not occur. This is a feature of the myopic characteristic of fishers' investment behaviour.

Table 2.1: The biomass nullcline

Biomass level	Region	The biomass nullcline
$0 < x < x^a$	Region 1	$K = \frac{r}{q} \left(1 - \frac{x}{\bar{x}} \right)$
$x^a < x < x^b$	Region 1	$\lim_{\phi \rightarrow 0} K = \infty$
$x^b < x < \bar{x}^-$	Region 1	$K = \frac{r(1-x/\bar{x})(pqx-c)(\gamma+\delta)}{q[(pqx-c)-(1-\gamma)(\gamma+\delta)c_s]}$
$\bar{x}^- < x < \bar{x}^+$	Region 2	$K = \frac{r(1-x/\bar{x})(pqx-c)}{qc_l\gamma}$
$\bar{x}^+ < x < x^c$	Region3	$K = \frac{r(1-x/\bar{x})(pqx-c)(\gamma+\delta)}{q[(pqx-c)-(1-\gamma)(\gamma+\delta)c_l]}$
$x^c < x < \bar{x}$	Region3	$K = \frac{r}{q} \left(1 - \frac{x}{\bar{x}} \right)$

2.3 Results

The overarching aim of this essay is to explore the link between the extent of capital malleability and excess capacity in the case of the fishery with quasi-malleable capital. We do this, in the first instance, analytically through an examination of model equilibria, that is capital-biomass combinations for which there is simultaneous stability in the capital stock ($\dot{K} = 0$) and the biomass ($\dot{x} = 0$) of the fishery. Such equilibria are depicted in Figure 2.1 as the set of points along the biomass nullcline in Region 2. By contrast, in Regions 1 and 3, such equilibria cannot be found given that capital is either increasing or decreasing for all biomass levels in these regions. Equilibrium that lie on the positively sloped portion of the biomass nullcline in Region 2 are unstable in that minor perturbations in either the capital or biomass will result in further movements away from the equilibrium. We focus, therefore, on the set of stable equilibrium that lie on the negatively sloped portion of the Region 2 biomass nullcline.

An examination of Figure 2.1 indicates that the range of such biomass levels is determined by the relative positions of \bar{x}^- , \bar{x}^+ and x^G . For the case in which $x^G = 1/2[\bar{x} + c/(pq)]$ lies between \bar{x}^- and \bar{x}^+ , as in Figure 2.1, the range of stable biomass is positively related to the cost of fishing effort, c . In contrast, the range of stable biomass is narrowed for higher population carrying capacity, \bar{x} , catchability coefficient, q , and fish price, p . The equilibrium level of biomass in our model is greater than the level at the traditional bionomic equilibrium, x^a , because investment decisions are assumed to be costly in our model. In other words, our model retains the traditional bionomic equilibrium at x^a when the cost of investment is zero, i.e., $c_I = c_S = 0$

2.3.1 Excess capacity and quasi-malleable capital

Stable equilibria that lie on the negatively sloped portion of the Region 2 biomass nullcline are associated with varying levels of excess capacity, Φ . More formally, for stable equilibria in the biomass range between x^G and \bar{x}^+ , excess capacity ranges between a minimum of $\Phi_{\min} = 1 - \phi^{\max}$ and a maximum of $\Phi_{\max} = 1 - \phi^{\min}$, where ϕ^{\max} and ϕ^{\min} are the maximum and minimum steady state capacity utilisation ratios given as:

$$\phi^{\max} = \phi(x^G) = \min\left(\frac{2c_I\gamma}{pq\bar{x} - c}, 1\right) \quad (2.14)$$

$$\phi^{\min} = \phi(\bar{x}^+) = \frac{\gamma}{\gamma + \delta} \quad (2.15)$$

The maximum capacity utilisation ratio, ϕ^{\max} , and hence minimum excess capacity, Φ_{\min} , occurs at the biomass level x^G , which is the smallest biomass on the stable portion of the biomass nullcline. In contrast, the minimum capacity utilisation ratio, ϕ^{\min} , and hence maximum excess capacity, Φ_{\max} , occurs at the highest stable equilibrium biomass level \bar{x}^+ . Our results therefore suggest that the level of underutilised capacity and the biomass at the equilibrium are positively related in the fishery with quasi-malleable capital. However, as is evident from Figure 2.1, the equilibrium level of capital stock in the fishery increases with a decrease in the level of underutilised capacity. That is to say, the total fishing effort, ϕK ,

increases as the equilibrium capacity utilisation ratio increases and the associated increased fishing effort results in a smaller level of biomass at the equilibrium (Figure 2.1).

We also find from Equation (2.14) that the minimum level of excess capacity, Φ_{\min} , will be higher, and hence the range of possible equilibrium excess capacity smaller, the lower is the unit price of landed fish, p , or the higher is the cost per unit of fishing effort, c , for a fishery with a given carrying capacity and level of capital malleability. Furthermore, Equations (2.5) and (2.15) together indicate that $\phi^{\min} = c_s/c_I$, where c_s/c_I indexes the malleability of capital as discussed in the section of fishery profit and malleability of capital. The greater is the malleability of capital, therefore, the higher the minimum steady state capacity utilisation ratio, ϕ^{\min} , will be. That is to say, when capital is easier to adjust, as indicated in our model by a smaller wedge between the purchase and resale prices of vessels, the smaller is the maximum potential excess capacity, Φ_{\max} , in the fishery. When capital is perfectly malleable or $c_s/c_I = 1$, for instance, the existing capital will be fully engaged in harvesting.

2.3.2 Initial conditions and equilibrium excess capacity

The dynamics of the capital stock, K , and biomass, x , in our model are shown in the phase portrait in Figure 2.1 and discussed at the end of the model section. Casual observation of these dynamics suggest that the starting values of biomass, x_0 , and capital, K_0 , will determine both the trajectories and speed of adjustment of both variables and, therefore, uniquely identify the steady state level of excess capacity arising in the fishery. That is, the condition of the fishery at the point at which a race to fish and invest begins determines the level of excess capacity in the steady state.

We simulate a parameterised version of our model to investigate the nature of this relationship by calculating the equilibrium capacity utilisation ratio, ϕ^* , for different combinations of the initial capital stock, K_0 , expressed in terms of standardised vessel units ranging from 10 to 500, and the initial biomass, x_0 , in terms of the proportion of the environmental carrying capacity⁸. Each simulation is conducted for 1000 periods to ensure that the fishery converges to the steady state. Benchmark parameter values are reported in Table 2.2. The parameter values for p , q , c , r and \bar{x} are from Bjørndal and Conrad (1987) and the remaining parameters, c_I , c_S , γ , and δ , are from Singh et al. (2006).

Table 2.2: Model parameterisation

Parameter	Value	Description
p	36.68	Price per tonne (\$)
q	6.77×10^{-4}	Catchability coefficient
c	38895	Cost per unit of fishing effort (\$)
γ	0.100	Depreciation rate of capital stock
δ	0.048	Time discount rate
r	0.800	Intrinsic growth rate
\bar{x}	3200000	Environmental carrying capacity (tonnes)
c_I	236500	Purchase price of capital (\$)
c_S	159800	Resale price of capital (\$)

⁸ It seems reasonable to analyse the adjustment of the fishery from a variety of initial conditions given we know that a large number of vessels are mobile between fisheries worldwide. When capital migrates into a fishery it can be pushed away from the adjustment path it would have taken from its “previously unexploited” state (i.e. $x_0 = \bar{x}$ and $K_0 = 0$).

Figure 2.2: Steady state capacity utilisation ratio for different initial biomasses and capital stocks.

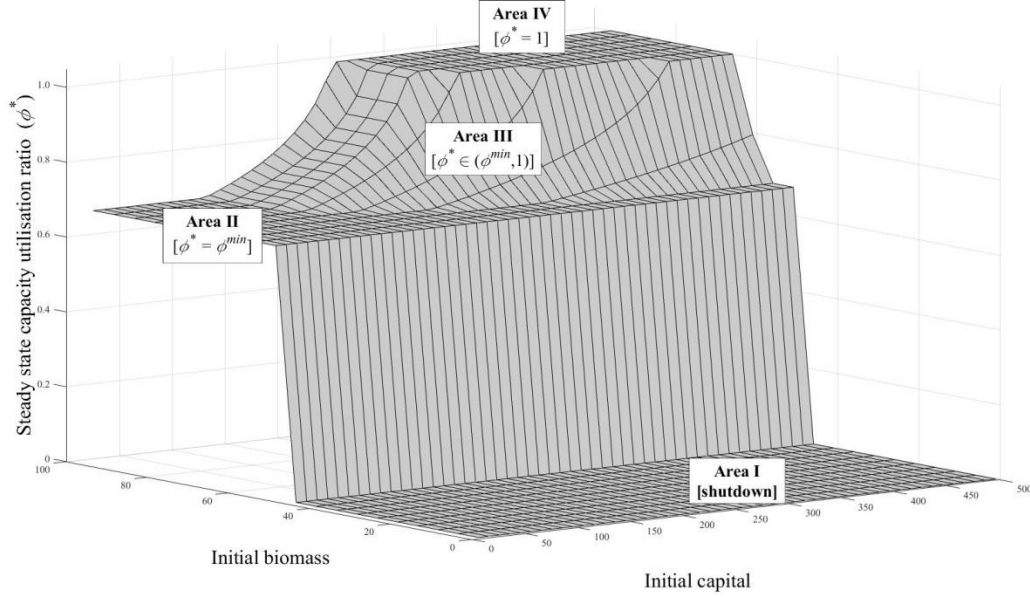


Figure 2.2 presents the steady state capacity utilisation ratio for different combinations of the initial capital stock and biomass. The surface in Figure 2.2 comprises four distinct Areas, I, II, III and IV. In Area I where the initial biomass is below the traditional bionomic equilibrium $x_0 < x^a = 0.46\bar{x}$, regardless of the size of the initial capital stock, the fishery shuts down due to negative returns to current capital, resulting in no capital stock in the fishery and therefore zero capacity utilisation. The surface plot in Figure 2.2 demonstrates an increasing relationship between both the initial biomass and capital stock of the fishery, and the steady state capacity utilisation ratio, ϕ^* . That is, the higher initial levels of the biomass and capital stock correspond to greater levels of capacity utilisation ratio and, therefore, less excess capacity in the fishery. For instance, Area IV represents combinations of initial capital stock

and biomass that result in $\phi^* = 1$ and no excess capacity in the steady state. In Area IV, the high initial values of the biomass and capital stock will mean higher levels of new investment and therefore greater depletion of the biomass (Region 3 in Figure 2.1), and this eventually causes the average return to current capital, $\bar{\mu}$, to fall below the resale price of fishing vessels, c_s . The underutilised capital will then be sold off and the fishery will equilibrate with full capacity utilisation at $\phi^* = 1$.

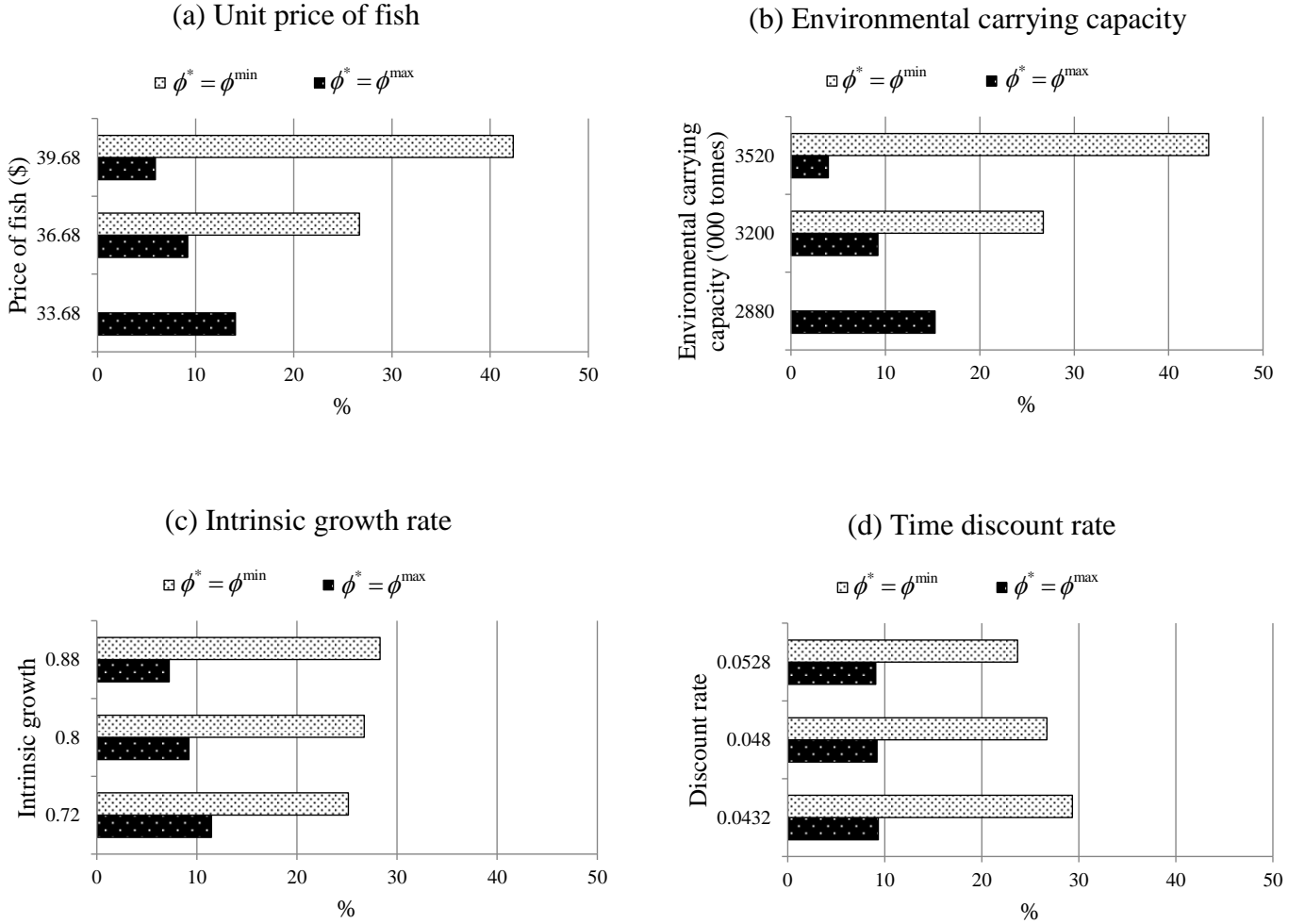
Figure 2.2 further shows that the maximum excess capacity at $\phi^* = \phi^{min} = 67.6$ percent occurs in the plateau of Area II, which represents about 23.0 percent of the set of initial values of the fishery examined in this essay. Furthermore, when the initial biomass is above 51.0 percent of the environmental carrying capacity, $x_0 > 0.51\bar{x}$, increasing the initial capital will increase the steady state capacity utilisation ratio up the ridgeline in Area III toward full capacity on the plateau in Area IV. For example, when the initial level of biomass is 76.0 percent of the carrying capacity, $x_0 = 0.76\bar{x}$, an initial capital of $K_0 < 130$ will result in $\phi^* = \phi^{min} = 67.6$ percent in Area II, whereas an initial capital of $K_0 = 230$ will lead to the higher capacity utilisation ratio of $\phi^* = 81.1$ percent in Area III. If the initial capital stock further increases to $K_0 > 280$, an initial biomass of $x_0 = 0.76\bar{x}$ will give rise to an equilibrium with full capacity, $\phi^* = 1$, on the plateau of Area IV.

2.3.3 Sensitivity analysis

Equilibrium outcomes in the fishery, for key fisheries variables such as biomass, effort and harvest, have been shown to be sensitive to changes in biological and economic parameters in fisheries bioeconomic models (Gordon, 1954, Smith, 1969, Bjørndal and Conrad, 1987).

Thus, we analyse the sensitivity of the steady state capacity utilisation ratio, ϕ^* , to four key parameters, namely the price of fish, p , the environmental carrying capacity, \bar{x} , the intrinsic growth rate, r , and the time discount rate, δ . Specifically, we calculate the proportion of the simulated trajectories corresponding to different initial conditions in the fishery that culminate in the maximum steady state capacity utilisation ratio, $\phi^* = \phi^{\max}$ (Area IV) and the minimum capacity utilisation ratio, $\phi^* = \phi^{\min}$ (Area II) for a 10.0 percent increase and decrease in the base case value for each of the parameters, p , \bar{x} , r , and δ .

Figure 2.3: Sensitivity analysis of steady state capacity utilisation ratio: the percentage of simulated trajectories stabilising with $\phi^* = \phi^{\min}$ or $\phi^* = \phi^{\max}$ for variation in the parameter values



Panels (a) and (b) of Figure 2.3 show that increasing the unit price of landed fish, p , or the environmental carrying capacity, \bar{x} , decreases the proportion of trajectories achieving the maximum steady state capacity utilisation ratio $\phi^* = \phi^{\max}$ and increases the proportion of trajectories achieving the minimum capacity utilisation ratio $\phi^* = \phi^{\min}$. In other words, the

higher the price of fish or the greater the maximum size of the population, the greater the likelihood of the steady state capacity utilisation ratio being either $\phi^{\min} < \phi^* < 1$ or $\phi^* = \phi^{\min}$ and therefore the higher the potential for excess capacity in the fishery. Panel (c) shows a similar case where increases in the intrinsic growth rate, r , decrease the likelihood of $\phi^* = \phi^{\max}$ but increases the likelihood of $\phi^* = \phi^{\min}$. For instance, when the intrinsic growth rate is $r=0.72$, about 11.5 and 25.1 percent of the simulated trajectories achieve the maximum and minimum steady state capacity utilisation ratio respectively. By contrast, when the intrinsic growth rate increases to $r = 0.88$, the proportion of the simulated trajectories achieving the maximum and minimum steady state capacity utilisation ratio becomes 7.2 and 28.3 percent respectively.

In the case of the time discount rate, δ , Panel (d) of Figure 2.3 shows that lower values of the discount rate result in a greater proportion of the trajectories culminating in both the maximum and minimum capacity utilisation ratio, $\phi^* = \phi^{\max}$ and $\phi^* = \phi^{\min}$. These changes reflect the two effects a change in the time discount rate has on the steady state capacity utilisation ratio. When the discount rate decreases, *ceteris paribus*, fishers put more weight on future returns and the average return to capital increases as reflected in Equation (2.10). At the same time, however, decreasing the discount rate also increases the size of the resale price of capital relative to its purchase price, *ceteris paribus*, effectively making capital more malleable as reflected in Equation (2.5).

2.4 Conclusion

Managing fishing capacity remains one of the biggest issues facing fisheries managers worldwide (Lutchman and Hoggarth, 1999, FAO, 2008, OECD, 2009). While much of the recent literature focuses on measures aimed at reducing capacity (Clark et al., 2005, Squires, 2010, Pascoe et al., 2012), effective management also requires controlling the emergence of new capacity (FAO, 2008, OECD, 2009, Pomeroy, 2012, Salomon and Holm - Müller, 2013). Thus understanding the process whereby capital accumulates and excess capacity emerges, particularly in fisheries where incentives to race to fish and invest are pervasive, and where capital is quasi-malleable, remains an important and under-studied issue.

We address the need to understand this process in this essay by proposing a model that allows us to describe the dynamic process whereby excess capacity, measured as the level of underutilised current fishing capacity, emerges in a fishery when there is a wedge between the purchase and resale prices of capital and where capital depreciates. For the case in which fishers form expectations of future biomass and harvest myopically and where the well-documented race behaviour in common pool resources exists in the fishery, we show that the fishery will have multiple stable equilibria of the capital stock and biomass that are distinguished by a varying capacity utilisation ratio. Our model results reinforce the importance of capital malleability in explaining the possible state of equilibrium excess capacity in such fisheries, identifying a positive relationship between the minimum steady state capacity utilisation ratio in the fishery and the ease with which downward adjustments in the capital stock can be made. That is to say, the easier it is to dispose of underutilised capacity in a secondhand market, as indicated in our model by a smaller wedge between the purchase and resale prices of vessels, the smaller is the maximum potential level of excess

capacity in the fishery. The comparative statics of our analytical results indicate that, when capital is non-malleable, fisheries based on higher value species, with higher intrinsic growth rates or greater carrying capacity will be more susceptible to persistent, long run underutilised capacity as these conditions, that have been shown to strengthen the race to fish and lead to greater overexploitation (Clark, 2010), also fuel the race to invest and excess capacity.

Furthermore, the set of stable equilibria in our model reflects a range of possible outcomes in which high biomass and low capacity utilisation go hand in hand in the fishery where fishers engage in a race to fish and invest, indicating a possible trade-off between economic and conservation objectives. Our model shows that the problem of overexploitation in the fishery is underpinned by the large accumulated capital stock, but this does not correlate with the presence of high levels of excess capacity. This observation of a possible trade-off between excess capacity and stock size highlights the importance of understanding the dynamic process of capital accumulation across a range of institutional contexts, and under alternative assumptions about investment behaviour. Overall our results suggest caution in using the extent of excess capacity, as defined in this essay as the equilibrium level of underutilised capacity, as the sole indicator of the health or performance of the fishery (World Bank, 2012). For example, different methodologies have been developed to estimate the capacity utilisation of a fishery (Kirkley et al., 2002) and such methodologies have been used to evaluate the fishery performance as well as to assess the effects of changes to management, such as from command-and-control management to rights-based fisheries. However, our results suggest that such estimates alone should not be used to determine the state of the fishery in terms of the excess accumulation of capital stock.

Simulations of a parameterised version of our model further enabled us to explore the relationship between the level of equilibrium excess capacity in the fishery and the initial state of the fishery in terms of starting stocks of biomass and capital. Understanding this relationship will be particularly pertinent in cases where capacity management programs in fisheries with high levels of underutilised capacity result in the redeployment of displaced fishing capacity to other stocks or fisheries (Gréboval and Munro, 1999) or where climate change driven changes in the abundance and distribution of commercial fish stocks motivate the reallocation of fishing effort and capacity as fishers adapt (OECD, 2010). Our results indicate that, while higher initial levels of capital will result in more severe overexploitation and greater equilibrium capital stock, there is a negative relationship between the initial capital stock and the equilibrium level of excess capacity in the fishery. Applying a higher initial stock of capital to a biomass of given size will result in more overexploitation but also in less underutilised capacity in the fishery. Understanding this trade-off will help managers charged with rebuilding fisheries and managing fishing capacity.

Conventional bioeconomic models of fisheries assume perfectly malleable capital and do not help us to understand the process of capital investment and the development of excess capacity. While there are some studies dealing with fisheries with non-malleable capital (McKelvey, 1985, Eisenack et al., 2006), they are unable to account for the extent of excess capacity as their models assume that the existing capacity is either fully utilised or not utilised at all. We take a step in this essay toward developing this understanding by exploring the issue of excess capacity, or underutilised capacity, in the fishery with quasi-malleable capital. It is well known that the free-entry-and-exit nature of open access fisheries leads to over-investment in fishing capital, overexploitation of target and bycatch species and the dissipation of economic rent. We show that where capital is quasi-malleable, the open access

nature of the fishery also results in excess capacity. That is, rather than being a purely short run feature, even in equilibrium it is possible that fishing capacity remains underutilised in the fishery.

While implementing policies that address the root causes of excess capacity in fisheries by removing incentives that drive race to fish and to invest behaviour remains paramount, the question of how to manage existing excess capacity remains unclear. Our results suggest that increased utilisation of current capacity without eliminating the race behaviour would result in further overexploitation of already vulnerable stocks; yet, efforts to remove and or redeploy excess capacity may be costly and have the potential to exacerbate excess capacity in other fisheries. This observation reinforces the need to approach the problem of fisheries capacity management as an issue at the sectorial or multi-fishery, rather than single fishery, level (Holland, 1999) and makes the question of how best to manage existing capacity in such fisheries to meet economic, social and environmental goals, as they transition to regulated fisheries, of central importance. Furthermore, the importance of designing effective capacity management policies goes beyond the case of the fishery where the fishing regulations are either absent or ineffective as incentives to compete in harvesting and investment among fishers is evident in fisheries under a range of regulatory regimes, including individual transferable quotas (Costello and Deacon, 2007, Emery et al., 2014).

A number of limitations to our analysis suggest useful directions for future research. A key feature of our model is the assumption that fishers are myopic and that they form expectations of the average return to current capital based only on the current level of the biomass in deciding the level of capital investment or disinvestment. While this assumption is consistent with the spirit of open access resource use, incorporating alternative ways in which

fishers form expectations (Holland, 2008) into harvesting and investment behaviour would be useful. In addition, and as called for by Nøstbakken et al. (2011), exploring the effect on the development of capacity of alternative investment rules or heuristics, reflecting alternative types of fishery business organisations would be useful. Finally, our model of capital accumulation in the fishery is deterministic and as such does not account for the high levels of natural variability that are characteristic of many fish populations (Caddy and Gulland, 1983, Hofmann and Powell, 1998). For example, when the fish stock is subject to natural fluctuations, some level of excess capacity is acceptable or even desirable in the fishery where the fishing effort and investment rate are controlled optimally (Poudel et al., 2013); yet, it is unclear whether excess capacity, which is ultimately developed through the race to invest behaviour, is similarly acceptable, or if not, what the economic costs or benefits with the development of such excess capacity would be. The extension of our work to incorporate the effects on the capital stock and excess capacity of uncertainty, in particular environmental variation, is needed.

Chapter 3. Excess Capacity and Environmental Variation in Open Access Fisheries

3.1 Introduction

Many fisheries are subject to fluctuating environmental conditions that lead to changes in the recruitment of the fishery (Reed, 1974, Reed, 1979, Clark, 2010, Kuparinen et al., 2014, Lehodey et al., 2006, Walther et al., 2002). In upwelling systems, for instance, many fish populations exhibit spawning strategies that are affected by the seasonal fluctuations in enrichment, concentration and retention that characterise such systems (Walther et al., 2002, Lehodey et al., 2006, Picaut, 1983, Adamec and O'Brien, 1978, Lewis, 1981, Shannon, 1985, Shillington, 1998). There is also growing evidence that the recruitment of fisheries is subject to dramatic and long-lasting changes that reflect underlying shifts in the state of the ecosystem (Ling et al., 2015, Möllmann and Diekmann, 2012, Miller et al., 1994, Hare and Francis, 1995, Russell et al., 1971).

It is commonly understood that excess capacity¹ in fisheries is linked to changes in environmental conditions (Ward et al., 2005, Squires et al., 2003).² However, papers which

¹ In this essay, as in Chapter 2 of this thesis, fishing capacity refers to the ability of the fleet to harvest fish, and is measured as the maximum harvest of the fishery given normal or customary operating conditions, when the variable inputs to production are fully utilised (Pascoe et al., 2003). Excess capacity occurs when the harvest of the fishery is lower than the capacity harvest of the fishery.

explicitly model the connection between environmental variation and excess capacity are rare. In an open access fishery that is subject to environmentally-driven fluctuations in recruitment, Ludwig et al. (1993) describe a relationship between fluctuations in the abundance of fish and excess capacity. In a process termed ‘Ludwig’s ratchet’, episodes of favourable recruitment improve the harvest and encourage the accumulation of capacity. When the capital is non-malleable, meaning it cannot be immediately and costlessly adjusted, the capacity accumulated during favourable fishing conditions cannot be reversed when the recruitment returns to its ‘normal’ levels. This means that the newly acquired capacity contributes to the level of excess capacity in the fishery. Such behaviour in the open access fishery is associated with the well-known race to fish which also manifests as a pressure to invest (Weninger and McConnell, 2000, Branch et al., 2006). In this thesis we therefore characterise such behaviour as the race to invest.

In a model of the open access fishery, where such race behaviour is at its most intense, we investigate the link between different types of environmental variation and excess capacity. Using a variant of the traditional Gordon-Schaefer model we examine the effects of both ‘positive’ and ‘negative’ fluctuations in environmental conditions, which represent low-frequency increases or decreases in the level of recruitment respectively. These fluctuations occur over time increments that are of sufficient length for the biomass of the fishery to be

² The relationship between excess capacity and fluctuations in environmental or economic conditions in a sole owner fishery is described by Ward et al. (2005). In cases where fisheries regulations eliminate the race to fish, Ward et al. (2005) demonstrate that excess capacity is self-correcting over time.

stable at each point in time. In contrast to the traditional model, we represent the harvesting and investment decisions of the fishers as separate races, allowing us to measure the proportion of the current capacity engaged in harvesting via the capacity utilisation ratio. We assume the net revenue from harvesting is equal to zero, a condition that is consistent with the long-run equilibrium of the Gordon-Schaefer model (i.e. where the economic profit of the fishery is exhausted). This implies a certain level of capacity utilisation for the fishing fleet as a whole, and in our model this level is captured by the capacity utilisation ratio. To model the adjustment of the capital stock we adopt the investment rule described by McKelvey (1985) in which the capital stock expands up to the point at which the expected net present value of investment equals the purchase price of capital. We further assume that fishers form an expectation of the return to investment based only on the current fishing conditions, i.e. myopically (Berck and Perloff, 1984, Loewenstein et al., 2003, Loewenstein, 2000).³ These changes in the capital stock are modelled as ‘pulse’ investments. While gradual changes in capital may be observed over finer time-scales, all changes in capital appear as ‘instantaneous’ in the long-run model considered for this paper.

To the best of our knowledge the analysis presented in this essay represents the first explicit investigation of the link between excess capacity and environmental variation in fisheries where the race to fish and the race to invest are prominent. We undertake an analysis for two types of capital: i) perfectly non-malleable capital, which does not depreciate and cannot be

³ As discussed in the introduction to this thesis, this form of myopia is symptomatic of a phenomenon called ‘projection bias’, where individuals perceive themselves in the future as being much the same as themselves in the present, and therefore place an overemphasis on the present conditions in their decision-making behaviour (Loewenstein et al., 2003).

disinvested; and ii) quasi non-malleable capital, which does depreciate over time but cannot be disinvested (Clark, 2010, Clark et al., 1979). We first investigate the persistence of excess capacity as a result of transient fluctuations in environmental conditions, during which the recruitment increases or decreases to a new level before returning to the original (‘normal’) state. In a parameterisation of our model with quasi non-malleable capital, we further investigate excess capacity for regular cyclical fluctuations in recruitment and also in the case of both ‘positive’ and ‘negative’ regime shifts, where the recruitment of the fishery permanently increases and decreases respectively. As a baseline for our analyses we assume an initial state in which recruitment is at its long-term ‘average’ level and a single fishing vessel is active in the fishery.

3.2 The model

3.2.1 Recruitment and environmental variation

We assume a logistic specification of density dependent growth for the fishery’s biomass, $G(\cdot)$, shown below as:

$$G(x_t) = z_t \cdot r x_t \left(1 - \frac{x_t}{\bar{x}} \right) \quad (3.1)$$

where x_t is the total biomass of the fish stock (in tonnes) at time t , r is the intrinsic growth rate of the fishery and \bar{x} is the environmental carrying capacity. The variable z_t captures the effect of environmental variation on the growth of the fishery's biomass. We assume initially that the value of z_t is one, which represents the long run average ('normal') level of recruitment. A positive fluctuation in z_t (i.e. $z_t > 1$) reflects a favourable change in the environmental conditions and results in an increase in the recruitment of the fishery, and this represents a period of high growth in the biomass. Conversely, when negative fluctuations occur (i.e. $0 < z_t < 1$) the recruitment of the fishery decreases and this results in a period of slower growth in the biomass. We use the variable z_t to capture different types of environmental variation. In particular we explore three different scenarios for the fluctuations in recruitment. These are: i) transient fluctuations in which a single-episode of either higher or lower recruitment occurs; ii) regular fluctuations in which recruitment moves up and down according to a regular cycle in the environmental conditions; and iii) both positive and negative 'regime shifts' where recruitment permanently increases or decreases in the fishery (Lehodey et al., 2006, Kuparinen et al., 2014, Walther et al., 2002).

3.2.2 Investment in open access fisheries

In race to fish fisheries where fishers are also engaged in the race to invest, capital investment (I_t) occurs through a series of changes in the capital stock (K_t), during which fishers equate the expected net present value of a unit of investment at time t , $\bar{\mu}_t$, with the purchase price of capital, c_t (McKelvey, 1985). When investing in new capital is profitable, i.e. $\bar{\mu}_t > c_t$, fishers replace depreciated capital and purchase extra capital so that $\bar{\mu}_t$ is equal to the purchase price of capital c_t . When such investment is not profitable, i.e. $\bar{\mu}_t < c_t$, no new capital will be purchased and any depreciated capital will not be replaced, so that the

level of investment $I_t = 0$. If $\bar{\mu}_t$ is equal to the purchase price of capital (i.e. $\bar{\mu}_t = c_t$) then fishers maintain the current level of capital by replacing depreciated capital so that $I_t = \gamma K_t$, where γ is the rate of depreciation.

Following McKelvey (1985) we specify $\bar{\mu}_t$ as:

$$\bar{\mu}_t = \int_0^{\infty} \frac{h_{\tau}^e}{K_{\tau}^e} \left(p - \frac{W(x_{\tau}^e, h_{\tau}^e)}{h_{\tau}^e} \right) e^{-(\gamma+\delta)(\tau-t)} d\tau \quad (3.2)$$

where x_{τ}^e , K_{τ}^e and h_{τ}^e are the expected levels of the biomass, capital stock and harvest, respectively, for the future time periods $\tau > t$; and p is the unit price of fish and $\delta \geq 0$ is the time discount rate. $W(x_{\tau}^e, h_{\tau}^e)$ is the expected total cost of harvesting for the future time periods $\tau > t$.

Since the future time paths of x_{τ} , K_{τ} and h_{τ} are not known for all $\tau > t$ at time t , the expected net present value of a unit of investment at t depends on fishers' expectations of the future. As in the first essay of this thesis (Chapter 2), we adopt a form of myopic behaviour known as 'projection bias' where the fishers interpret themselves in the future as being the same as themselves in the present, and therefore place an over-emphasis on the current conditions in their decision-making process (Loewenstein et al., 2003, Loewenstein, 2000). As discussed in the introduction to the thesis, the near-sighted (i.e. myopic) behaviour of fishers is central to the race to fish and the race to invest in the fishery. In circumstances

where such race behaviour is prominent, the fishers will expect future levels of the biomass, the capital stock and the harvest to be the same as in the present, i.e. $x_t^e = x_t$, $K_t^e = K_t$ and $h_t^e = h_t$ for all $\tau > t$, and the expected net present value of a unit of investment will be:

$$\bar{\mu}_t = \frac{\frac{h_t}{K_t} \left(p - \frac{W(x_t, h_t)}{h_t} \right)}{\gamma + \delta} \quad (3.3)$$

In contrast to McKelvey (1985), who assumes the full utilisation of capital for all t , we allow the fishing capital to be used at a proportion of its fishing capacity, so that $0 \leq \phi_t \leq 1$ is the capacity utilisation ratio and the level of fishing effort $E_t = \phi_t K_t$ represents the proportion of the existing capital that is engaged in harvesting. Given this, the harvest in the fishery is

$h_t = qx_t \phi_t K_t$ where q is the catchability coefficient (Schaefer, 1957). We specify the total cost

of harvesting in the present period t as $W(x_t, h_t) = ch_t / (qx_t)$ where c is the cost per unit of

fishing effort. Since we specify a long-run model of the fishery, we assume all costs are

variable. However a limitation of this approach is that we cannot distinguish between effort

levels E_t that are driven by the capital stock K_t and those which are mostly due to the

capacity utilisation ratio ϕ_t , and the different implications these situations have for the total

cost of fishing effort. Our total cost function assumes constant returns to scale (i.e. $W_{h_t} > 0$

and $W_{h_t h_t} = 0$), so that the marginal harvesting cost ($c / (qx_t)$) is unchanged by the harvest h_t .

It also captures the stock externality effect via an increase in the marginal harvesting cost at

lower biomass levels (i.e. $\frac{d[c/(qx_t)]}{dx_t} < 0$). Substituting the total cost of harvesting at time t ,

$W(x_t, h_t)$, and the harvest, $h_t = qx_t\phi_t K_t$, into Equation (3.3) gives the expected net present value of a unit of investment at time t :

$$\bar{\mu}_t = \frac{(pqx_t - c)\phi_t}{\gamma + \delta} \quad (3.4)$$

This specification of the expected net present value of a unit of investment at time t is distinguished from that given at Equation (2.10) in Chapter 2 by the assumption that the capacity utilisation ratio ϕ_t is both known and accounted for by fishers at the time of investment. Since the model in the current chapter is a static model, with a static level of capacity utilisation, we assume the sustained level of capacity utilisation will be recognised by fishers at the time of their investment (in the same way as the biomass is known at this time). In contrast, the omission of ϕ_t from Equation (2.10) is equivalent to assuming that it is one, i.e. the fishers who are entering the fishery at a given time expect that *their* capital, at least, will operate at its capacity.

In the race to fish fishery, the capacity utilisation ratio will be at full capacity ($\phi_t = 1$) when the net revenue from harvesting is positive (i.e. $pqx_t\phi_t K_t - c\phi_t K_t > 0$) or equivalently, from Equation (3.4) above, whenever $\bar{\mu}_t > 0$. Substituting $\phi_t = 1$ into Equation (3.4), the biomass

of the fishery when the investment in capital has ceased (i.e. when $\bar{\mu}_t = c_I$) can be found as

$x_t^* = \frac{(\gamma + \delta) \cdot c_I + c}{pq}$. The biomass is stable at this point (i.e. $x_{t+1} = x_t$) so that the equilibrium

condition $x_t = \bar{x} \left(1 - \frac{qE_t}{z_t r} \right)$ applies, where the level of fishing effort $E_t = \phi_t K_t$. As stated above,

the capacity utilisation ratio $\phi_t = 1$, so that $E_t = K_t$ and the level of capital K^* that exists

when investment has ceased is:

$$K^* = \frac{z_t \cdot r}{pq^2 \bar{x}} \cdot [(pq\bar{x} - c) - (\gamma + \delta)c_I] \quad (3.5)$$

In our model, the change in capital occurs instantaneously, via a ‘pulse’ of investment I_t , so that $K_{t+1} = K^*$. Given the standard capital dynamics, $K_{t+1} = K_t - \gamma K_t + I_t$, Equation (3.5), and the investment process discussed at the beginning of this section, a full specification of the investment rule in our model, with quasi non-malleable capital, is shown below:

$$I_t = \begin{cases} \frac{z_t \cdot r}{pq^2 \bar{x}} \cdot [(pq\bar{x} - c) - (\gamma + \delta)c_I] - K_t + \gamma K_t & \bar{\mu}_t > c_I \\ \gamma K_t & \bar{\mu}_t = c_I \\ 0 & \bar{\mu}_t < c_I \end{cases} \quad (3.6)$$

3.2.3 Excess capacity in race to fish fisheries

As discussed in the introduction to this thesis, excess capacity is defined as any situation in which the capacity utilisation ratio, ϕ_t , is less than one. In race to fish fisheries, fishers will operate their capital up to the point at which the gains from harvesting have been exhausted, i.e. where the net revenue from harvesting $pqx_t\phi_t K_t - c\phi_t K_t = 0$. Given the average return to a unit of investment $\bar{\mu}_t$ in Equation (3.4), the net revenue from harvesting will be zero when $\bar{\mu}_t = 0$, at which point we denote $\phi_t = \hat{\phi}_t$. The capacity utilisation ratio has an upper bound at $\phi_t = 1$, which corresponds to full capacity utilisation, so that the level of ϕ_t can be formalised as:

$$\phi_t = \min(1, \hat{\phi}_t) \quad (3.7)$$

Given Equations (3.4) and (3.7), the analytical expression for ϕ_t is shown below (a full derivation is in the appendix to this essay).

$$\phi_t = \begin{cases} 1 & z_t \geq \frac{pq^2 \bar{x} K_t}{r.(pq\bar{x} - c)} \\ \frac{z_t.r.(pq\bar{x} - c)}{pq^2 \bar{x} K_t} & 0 < z_t < \frac{pq^2 \bar{x} K_t}{r.(pq\bar{x} - c)} \end{cases} \quad (3.8)$$

The analytical expression in Equation (3.8) is for a given level of the capital stock K_t . The capital stock K_t is an endogenous variable that is determined by fishers' investment decisions, which in turn are influenced by the environmental variation captured by variable z_t . However, for a given level of K_t , the two cases of Equation (3.8) show a threshold level of environmental variation beyond which capacity is at least temporarily fully utilised in the fishery (i.e. $z_t \geq \frac{pq^2\bar{x}K_t}{r.(pq\bar{x} - c)}$). This threshold will be low for species where either the intrinsic growth rate (r) or the environmental carrying capacity (\bar{x}) are high, and also in cases where the price of fish (p) is high. The threshold will be high when the cost per unit of fishing effort (c) is high. In the case of the catchability coefficient q , the threshold decreases as q increases up until $q = 2c/p\bar{x}$, after which the threshold increases as q increases.

3.3 Results

The central aim of this essay is to investigate the link between excess capacity and environmental variation in a fishery where the race to fish and the race to invest are prominent, and in which capital is non-malleable. In achieving this aim, we first analyse transitory environmental variations in the fishery with both perfectly non-malleable capital (i.e. $I_t \geq 0$ and $\gamma = 0$), and quasi non-malleable capital ($I_t \geq 0$ and $\gamma > 0$). We then use parameterised simulations of our model to investigate the response of excess capacity to both regular cyclical fluctuations in recruitment as well as permanent 'regime shifts' which cause changes in the 'normal' level of recruitment in the fishery. As a baseline for our

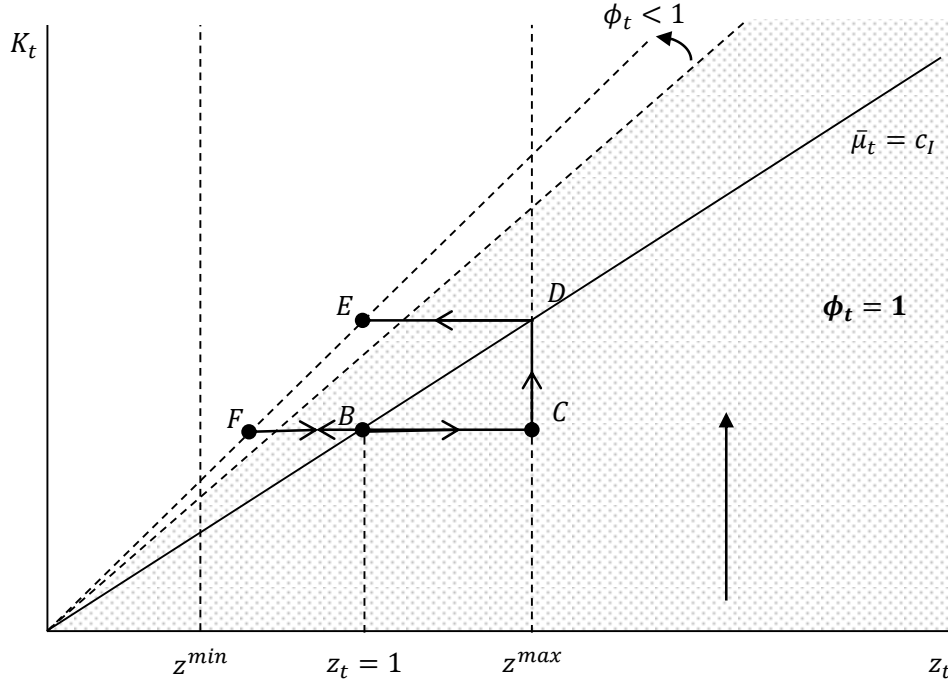
analyses we assume an initial state in which recruitment is at its ‘normal’ level (i.e. $z_t = 1$) and there is a single vessel harvesting from the resource (i.e. $K_0 = 1$).

3.3.1 Transient environmental variation and excess capacity

3.3.1.1 Perfectly non-malleable capital

A diagram showing the possible states of the fishery with perfectly non-malleable capital is presented in Figure 3.2, where the values of the state variables K_t and z_t are represented by the vertical and horizontal axes, respectively. The extent of environmental variation is bounded between the maximum and minimum values, z^{max} and z^{min} , as indicated on the horizontal axis by the dashed vertical lines.

Figure 3.2: The adjustment of the fishery between static equilibria when capital is perfectly non-malleable



For the combinations of capital and environmental variation above the curve labelled $\bar{\mu}_t = c_I$ in Figure 3.2 the expected net present value of investment $\bar{\mu}_t$ is less than the purchase price of capital c_I and the capital stock is stable due to it being perfectly non-malleable. By contrast, for the combinations of K_t and z_t below $\bar{\mu}_t = c_I$ the capital stock increases because the expected net present value of investment exceeds the purchase price of capital, $\bar{\mu}_t > c_I$. In this case a pulse of investment in the capital stock will occur instantaneously which brings the fishery on to the curve $\bar{\mu}_t = c_I$, as described in Equation (3.5). This investment is illustrated by the vertical arrow below the curve $\bar{\mu}_t = c_I$.

The extent of excess capacity in Figure 3.2 is identified by the dashed rays that extend from the origin, and along which the variables K_t and z_t give the same value of the capacity utilisation ratio ϕ_t . Rays which lie above the ray $\phi_t = 1$ identify values of capacity utilisation $\phi_t < 1$. All combinations of K_t and z_t below the ray $\phi_t = 1$, in the shaded area of Figure 3.2, are associated with the full utilisation of existing capacity, i.e. no excess capacity in the fishery.

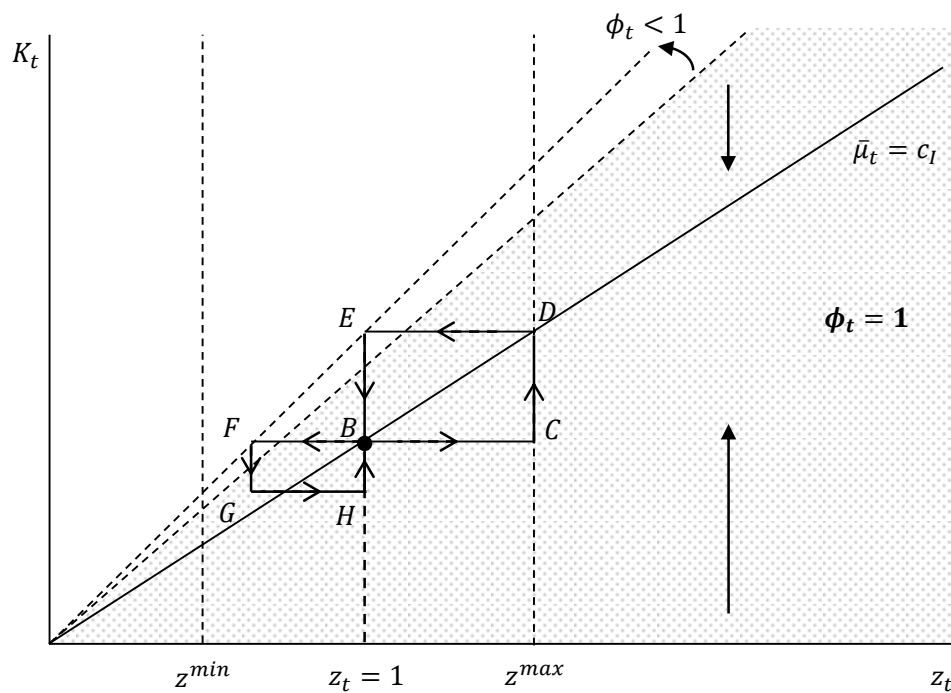
The adjustment process for the case of a positive fluctuation in the recruitment of the fishery is illustrated by the path B C D E in Figure 3.2. Beginning from point B, where $\bar{\mu}_t = c_t$, a subsequent positive recruitment fluctuation moves the fishery to C, where there is further investment that takes the fishery to D as shown in Equation (3.5). When environmental conditions return to ‘normal’ (i.e. $z_t = 1$) the fishery transitions to the point E, which marks the end of the fishery’s adjustment to equilibrium. This equilibrium is characterised by excess capacity ($\phi_t < 1$) which will persist in the absence of further environmental changes.

Again starting at the point B, the adjustment of the fishery in response to a negative recruitment fluctuation is shown in Figure 3.2 by the path B F B. The negative fluctuation in recruitment initially shifts the fishery leftwards to the point F, which is on a higher ray along which $\phi_t < 1$ and there is thus excess capacity. When the recruitment returns to ‘normal’ (i.e. $z_t = 1$) the fishery then moves back to full capacity utilisation at point B. Thus a negative recruitment fluctuation in the open access fishery with perfectly non-malleable capital will cause temporary excess capacity, but will not lead to permanent excess capacity.

3.3.1.2 *Quasi non-malleable capital*

Figure 3.3 presents a diagram showing the case of the fishery with a quasi non-malleable capital stock, similar to that discussed previously in the case of perfectly non-malleable capital. However in this case, when the fishery is at a point above the $\bar{\mu}_t = c_t$ curve the fishers allow their existing capital to depreciate at the rate $\gamma > 0$ as shown by the downward arrow in Figure 3.3 above the $\bar{\mu}_t = c_t$ curve.

Figure 3.3: The adjustment of the fishery between static equilibria when capital is quasi non-malleable



The fishery's response to a positive fluctuation in environmental conditions is shown by the path B C D E B in Figure 3.3. Starting from the initial point B, a positive fluctuation in recruitment moves the fishery out to point C, where there is a further burst of investment to point D. When the recruitment returns to normal (i.e. $z_t = 1$) the fishery transitions from D to E, where the capacity utilisation ratio $\phi_t < 1$ and there is thus excess capacity. The quasi non-malleable capital then depreciates and the system returns to the point B, where there is no excess capacity.

The fishery's response to a negative recruitment fluctuation is also shown in Figure 3.3 by the loop B F G H B. Again, starting from point B, the fishery initially moves to point F in response to the negative fluctuation in recruitment, and this is located on a ray for which $\phi_t < 1$ (i.e. excess capacity). Since the point F is above the curve $\bar{\mu}_t = c_I$, which denotes stable levels of the capital stock, the fishers will allow capital to depreciate and the fishery will move to the point G. When z_t returns to normal ($z_t = 1$), the fishery then transitions to point H, where the expected net present value of investment $\bar{\mu}_t > c_I$ (i.e. below the $\bar{\mu}_t = c_I$ curve). Consequently there is a burst of investment at H which returns the fishery to point B.

In the case of transient fluctuations in environmental conditions, the fishery with quasi non-malleable capital can experience temporary excess capacity as the capital stock adjusts up or down in response to positive or negative variations in recruitment. Excess capacity in this case is a feature of the adjustment in fishing capacity as the system moves from one level of recruitment to another, and in the absence of further recruitment fluctuations presents only a temporary phenomenon.

3.3.2 Simulating excess capacity in the open access fishery with quasi non-malleable capital

In this subsection we investigate the development of excess capacity in response to fluctuations in the environmental conditions for an open access fishery with a quasi non-malleable capital stock. In particular, we simulate the evolution of the capital stock K_t and the capacity utilisation ratio ϕ_t for three scenarios that describe the variation in recruitment of the fishery. Using a vector of environmental variation $\underline{z} = \langle z_1, z_2, \dots, z_T \rangle$ we present simulation results that examine: i) regular fluctuations in recruitment that coincide with a cyclical variation in environmental conditions; ii) positive ‘regime shifts’ in which the fishery’s recruitment permanently increases; and iii) negative ‘regime shifts’ in which the fishery’s recruitment permanently decreases.

Benchmark parameter values for our simulations are shown in Table 3.1.⁴ The values for p , q , c , r and \bar{x} are from Bjørndal and Conrad (1987), and the remaining parameters c_t and δ were obtained from Singh et al. (2006). We set the capital depreciation rate $\gamma = 0.05$. All simulations in this subsection are for 100 periods and assume an initial capital stock $K_0 = 1$, where the capital stock is measured in standard vessel units, and initial recruitment fluctuation of $z_t = 1$ (i.e. recruitment is at its ‘normal’ level). In our simulations, each period

⁴ All currencies are measured in United States dollars. Figures in Norwegian Kroner for the North Sea Herring were converted at a rate of 7.1429 Kroner to 1 United States dollar (University of British Columbia PACIFIC Exchange Rate Service, <http://fx.sauder.ubc.ca/etc/USDpages.pdf>).

represents a length of time that is sufficient to achieve stability in the biomass, and as such our analysis represents a comparison of the fishery at bioeconomic equilibria across time.

Table 3.1: Model parameterisation

Parameter	Value	Description
p	67.07	Price per tonne (\$)
q	6.77×10^{-4}	Catchability coefficient
c	38895	Cost per unit of fishing effort (\$)
δ	0.048	Time discount rate
r	0.800	Intrinsic growth rate
\bar{x}	3200000	Environmental carrying capacity (tonnes)
c_I	236500	Purchase price of capital (\$)

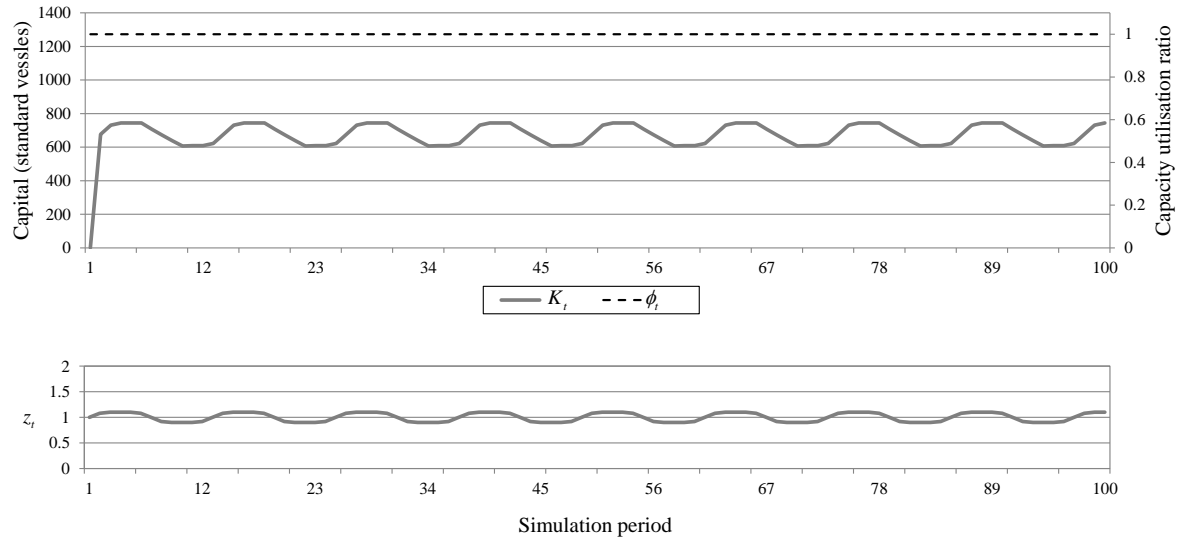
Note: The unit price of fish p in this essay is the average price, in U.S. Dollars, of North Sea Herring from 1963 to 1977 in the sample of Bjørndal and Conrad (1987). This contrasts with the unit price of fish in Chapter 2, which was for a specific year.

3.3.2.1 Cyclical fluctuations

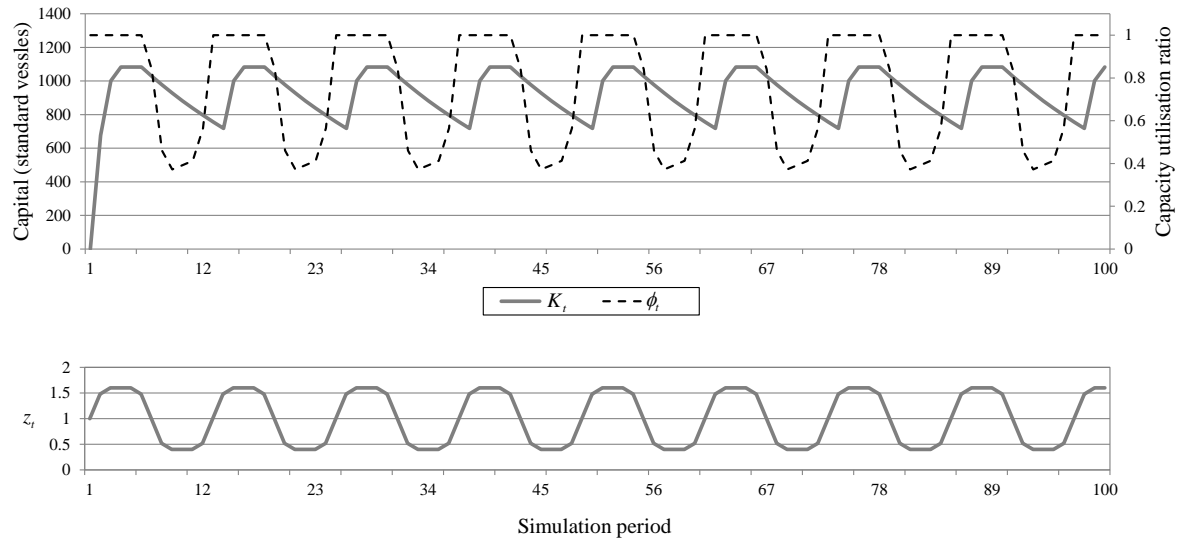
Figure 3.4 shows the behaviour of the capital stock K_t and the capacity utilisation ratio ϕ_t when environmental variation causes the recruitment to the fishery to cycle around a long run ‘normal’ level (at which $z_t = 1$).

Figure 3.4: Cyclical fluctuation in recruitment

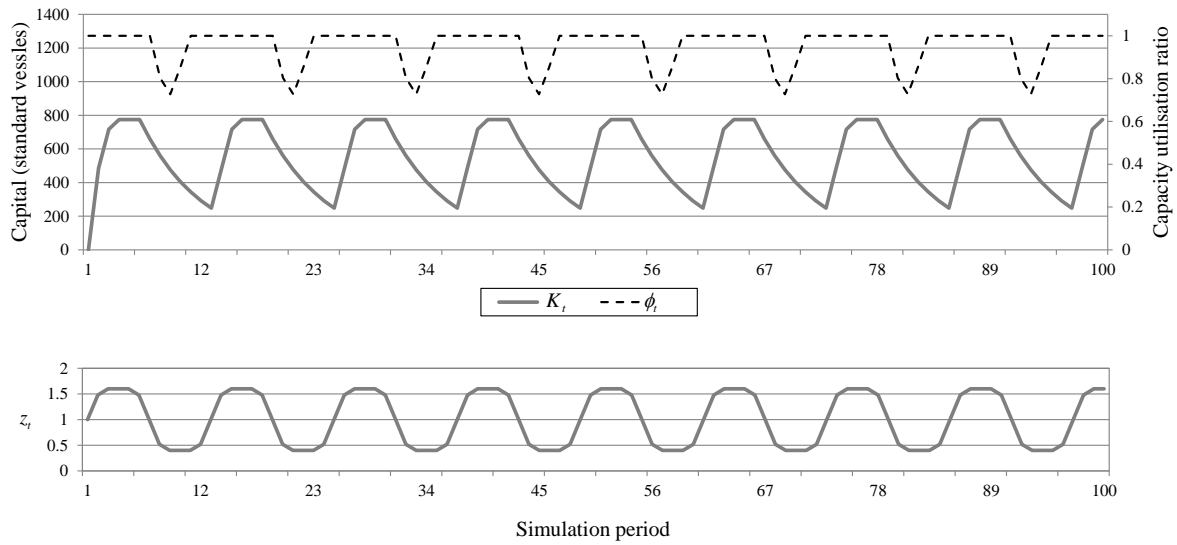
(a) 10.0 percent increase and decrease in recruitment for a depreciation rate $\gamma = 0.05$



(b) 60.0 percent increase and decrease in recruitment for a depreciation rate $\gamma = 0.05$



(c) 60.0 percent increase and decrease in recruitment for a depreciation rate $\gamma = 0.15$



Panel (a) of Figure 3.4 shows the behaviour of the capital stock and the capacity utilisation ratio for a cycle in recruitment of ± 10.0 percent above and below the ‘normal’ level; and Panel (b) shows the same fishery with a ± 60.0 percent cycle in recruitment. In both cases there is a regular process of investment and depreciation that occurs as the fishers capitalise the increased net revenue from harvesting that occurs during episodes of high recruitment, and then allow their capital to depreciate when recruitment decreases. When the magnitude of the environmental variation is sufficiently large, periodic episodes of excess capacity also result from the cycle in recruitment. This is shown in Panel (b), where the capacity utilisation ratio ϕ_t falls below 40.0 percent during the negative phase of the cycle (i.e. $z_t < 1$).

The pro-cyclical fluctuations in K_t are also larger when the environmental variation is higher. In Panel (b) the capital stock varies by approximately 44.0 percent in response to the recruitment fluctuations, where this is only around 20.0 percent in Panel (a). The comparison

of these two panels also demonstrates a relationship between the average size of the capital stock and the magnitude of the environmental variation. In particular, the average capital stock is higher when the variation in environmental conditions is larger. In Panel (a) the average capital stock during the recruitment fluctuations is 677 standard vessel units, whereas in Panel (b) this is around 934 standard vessel units. The increase in the expected net present value of investment ($\bar{\mu}_t$) during an episode of strong, environmentally driven recruitment is greater, and more capital is therefore purchased during the positive recruitment fluctuations (so that the average capital stock is higher when environmental variation is higher).

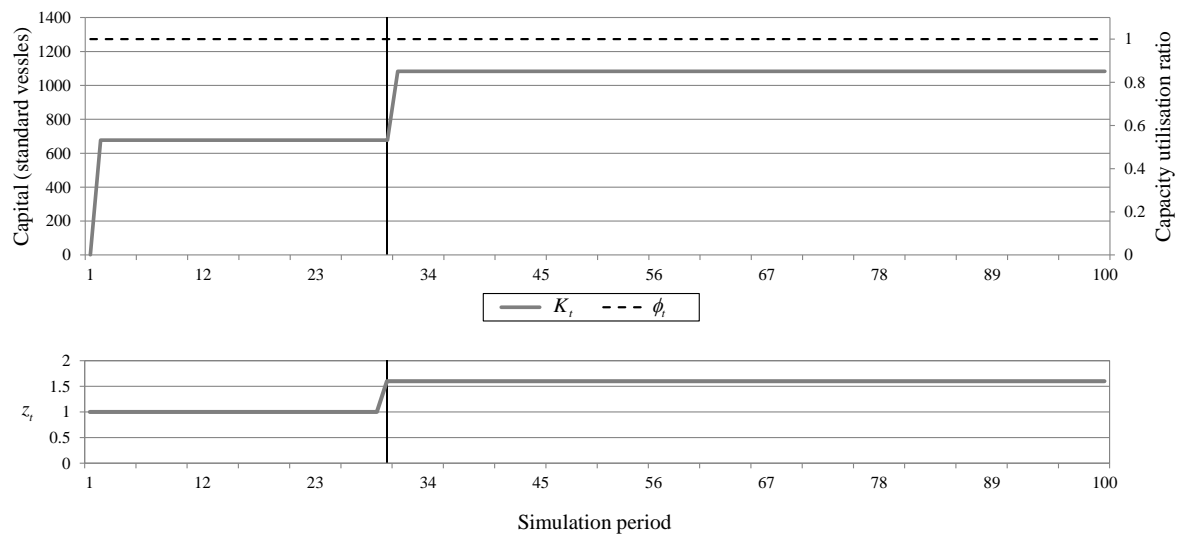
Panel (c) of Figure 3.4 shows the effect of the malleability of capital on the level of excess capacity. For an increased malleability of capital, as captured by a higher rate of depreciation ($\gamma = 0.15$), the results in Panel (c) suggest a link between the malleability of capital and the extent of excess capacity. As the rate of depreciation increases, the expected net present value of a unit of investment $\bar{\mu}_t$ decreases, so that less capital is purchased during favourable environmental conditions, and there is consequently a lower average level of capital in the fishery in Panel (c). The reduction in the capital stock during less favourable conditions is also greater when the depreciation of capital is higher, and as a consequence the size of the pro-cyclical fluctuations in K_t are greater in Panel (c) than in Panel (b). Therefore when the capital is more malleable, as denoted by a faster rate of depreciation, periods of excess capacity are less severe and the cycle of capacity utilisation is characterised by longer periods of full capacity ($\phi_t = 1$).

3.3.2.2 Regime shifts

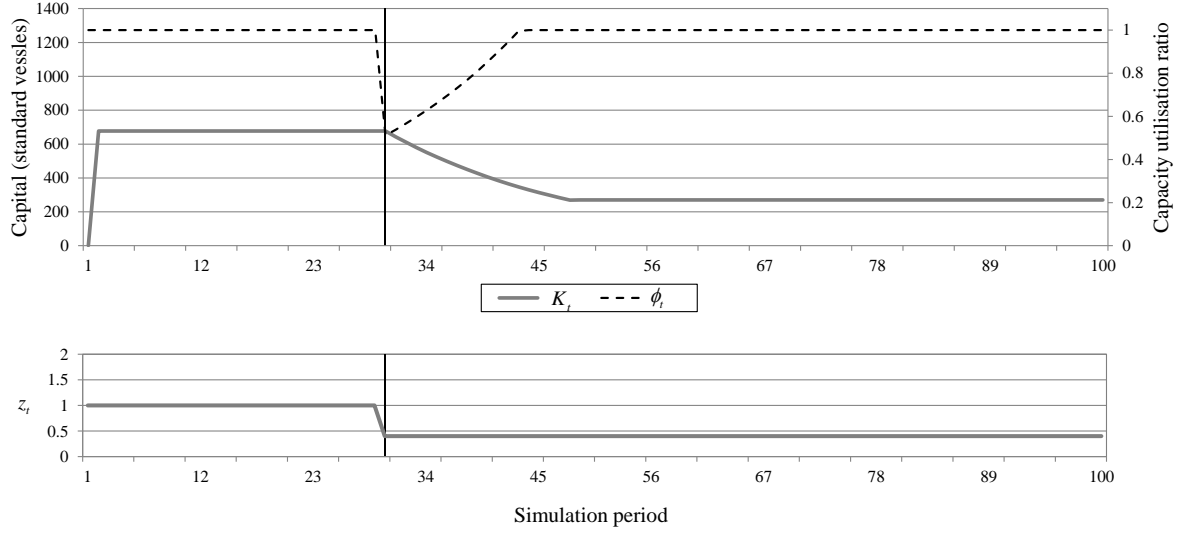
In Figure 3.5 we present results for positive and negative regime shifts in the fishery with quasi non-malleable capital. These regime shifts cause the recruitment of the fishery to change abruptly, and for a prolonged period of time, to higher and lower levels respectively (Möllmann and Diekmann, 2012, Ling et al., 2015, Miller et al., 1994, Hare and Francis, 1995). In our simulations, these regime shifts begin in period 30, as indicated by the solid vertical line in each of the panels of Figure 3.5, and represent a change in the fishery's recruitment of ± 60.0 percent.

Figure 3.5: Regime shift resulting in an increase and decrease in recruitment

(a) Sudden increase to a new regime



(b) Sudden decrease to a new regime



The fishery's response to a positive regime shift is shown above in Panel (a) of Figure 3.5.

This increase in recruitment causes the capital stock to increase, as fishers capitalise the gain in net harvesting revenue that occurs as a result of the higher abundance of fish. The higher level of production from the fishery also requires full capacity utilisation (i.e. $\phi_t = 1$), so that there is no excess capacity in response to positive regime shift. The fishery's response to a negative regime shift is shown in Panel (b) of Figure 3.5, which shows an abrupt drop in the recruitment of the fishery to a new lower level. In this case, the capital stock decreases as the fishers cease replacing depreciated capital to compensate for a reduction in net harvesting revenue (at the lower recruitment), and this adjustment results in a large episode of excess capacity ($\phi_t < 1$). In this case excess capacity is a temporary feature of the fishery, and is associated with the downward adjustment of the capital stock. The lower level of recruitment

is concomitant with a lower harvest in the fishery, and this requires less capital stock.

Changes in the harvest occur rapidly, but the adjustment of the capital stock requires a longer time since it occurs through the depreciation of capital. This creates a mismatch between the harvest and fishing capacity that is reflected in the level of excess capacity.

3.4 Conclusion

Excess capacity is often understood as a transitional feature of the fishery that is associated with the inability of the capital stock to adjust to fluctuations in economic and environmental conditions (Ward et al., 2005, Squires et al., 2003). However, in some circumstances the race to fish and race to invest can lead to persistent levels of excess capacity that result in economic waste in the form of underutilised capacity (Clark and Munro, 2002, Gréboval and Munro, 1999). Effective responses to such economic waste continue to elude fisheries managers and researchers alike (OECD, 2009, Salayo et al., 2008). An important step in developing better management practices for fisheries, which improve the allocation of scarce resources and reduce economic waste, can be made through a greater understanding of the drivers of wasteful excess capacity.

It has long been understood that deterministic models can give poor guidance on fisheries management decisions when environmental conditions fluctuate over time (Hannesson, 1987). In a theoretical model of the sole-owner fishery Charles (1983) and Charles and Munro (1985) show that the capital stock fluctuates over a broad range under stochastic assumptions. By way of comparison with our model, Panels (b) and (c) of Figure 3.4 indicate that this may also be true of the pure open access fishery with environmental variation. Charles (1985) finds that the capital stock in a sole-owner fishery decreases with higher rates of depreciation on

capital, and this also seems to be the case for the pure open access fishery, again by a comparison of Panels (b) and (c) of Figure 3.4. While these observations reveal some parallels between the change in the capital stock that occurs due to environmental variation in models of the sole-owner fishery, and the behaviour of capital in our model of the pure open access fishery with environmental variation, it is important to note that the sole-owner fishery represents optimal behaviour and is not directly comparable to the pure open access fishery, where the capital stock is a culmination of decisions that are motivated by an inefficient race to invest.

In this essay we explore the link between environmental variation and excess capacity using a bioeconomic model of the open access fishery in which myopic fishers invest up to the point at which they expect the expected net present value of a unit of investment to be equal to the purchase price of capital. The fishers' harvesting decision is modelled separately from their investment decision, and this is captured through the proportional utilisation of the current capacity. In our model we consider both perfectly non-malleable capital and quasi non-malleable capital (Clark et al., 1979), which represent degrees of adjustability of the capital stock. We investigate three types of environmental variation, which are: transient fluctuations, regular cyclical fluctuations and permanent regime shifts in which the fishery's recruitment moves from one level to another. These represent fluctuations in the recruitment of the fishery that result from changes in the physical environment.

Our results confirm a relationship between environmental variation, investment and excess capacity. In the fishery with perfectly non-malleable capital, when there is a transient positive fluctuation in recruitment the myopic fishers accumulate additional capital that will expand the fishery's capacity. When the fishing conditions return to 'normal' levels, this newly

acquired capital represents excess capacity. This process of capacity accumulation is consistent with the description of ‘Ludwig’s ratchet’ (Ludwig et al., 1993, Pitcher, 2001, Pinnegar and Engelhard, 2008). In Ludwig’s ratchet, fishers who purchase capital when the recruitment is high subsequently pressure authorities to provide subsidies that sustain the harvest when the fishing conditions return to ‘normal’. In the context of our model, such subsidies would encourage the utilisation of capacity by increasing the net revenue from harvesting. The resulting increase in the capacity utilisation ratio in turn causes an escalation of harvesting, which reduces the biomass of the fishery. Subsequent fluctuations in recruitment cause further ‘ratcheting’ down of the biomass, and potentially lead to the collapse of the fishery. In our model, for the case of quasi non-malleable capital, the new capacity acquired during positive recruitment fluctuations disappears over time due to the depreciation of capital. Consequently the increase in harvesting that occurs because of the higher capacity utilisation ratio diminishes over time, so that the fishery partially or completely self-corrects for the ratchet effect.

In the open access fishery with quasi non-malleable capital, our results also suggest that regular cyclical fluctuations in recruitment can lead to excess capacity. When fluctuations are of sufficient magnitude, periodic episodes of excess capacity will transpire during the negative phases of the recruitment cycle. Reductions in recruitment also generate excess capacity in the case of transient negative fluctuations as well as in the case of negative regime shifts. In the latter of these cases a permanent decrease in recruitment of the fishery leads to a protracted episode of excess capacity.

For all types of environmental variation explored in this essay, we find that the level of excess capacity is determined by the size of the environmental variation relative to the rate of

capital depreciation, or the level of capital malleability. A negative change in recruitment reduces the sustainable harvest of the fishery, which necessitates a reduction in the capital stock. While the harvest adjusts quickly through the utilisation of current capacity, the quasi non-malleable capital changes more gradually through the depreciation of capital and this disparity leads to a high level of excess capacity. As the rate of depreciation increases, which is to say that capital becomes more malleable, the episodes of excess capacity are smaller and of less duration. In contrast to negative changes in recruitment, positive regime shifts, which increase the level of recruitment in the fishery, do not cause excess capacity. The increase in recruitment increases the sustainable harvest of the fishery which leads to investment, but does not generate excess capacity since the newly acquired capital is appropriate for the new recruitment of the fishery after the regime shift.

In this essay we have shown how excess capacity can arise in the context of race to fish and race to invest behaviour, as a result of environmental variation and non-malleable capital.

Despite much progress in fisheries management world-wide, the race to fish continues to be a hallmark of common-pool resource use, even in cases where catch and effort are regulated, or where catch shares are assigned. Our focus in this essay on racing behaviour in terms of fisher's investment and on environmental variation is both novel and increasingly important as climate change generates the potential for no-analog variations in oceanic conditions and fish recruitment (Möllmann and Diekmann, 2012, Lehodey et al., 2006).

Our results demonstrate a complex relationship between environmental variation and excess capacity. We find the levels of excess capacity which occur in the fishery due to environmental variation are transitory, in that they are self-correcting over time, when capital is malleable. However, we also find that the significance of excess capacity depends critically

on the type fluctuation in environmental conditions. In the case of negative fluctuations, where the recruitment of the fishery decreases, we find that the transitory effect is short term and generates no change in the capital stock. In the case of positive fluctuations, however, the increase in the sustainable harvest of the fishery generates wasteful investments in capital that also contribute to rent dissipation in the fishery. When regular cyclical fluctuations occur over time, we find that the periodic increases in recruitment are associated with transitory economic waste, in the form of inefficient capital investments that are depreciated away over time.

Our results show that, in the presence of environmental variability, the malleability of the capital stock is a key determinant of the level of excess capacity in race to fish fisheries. When the capital stock is highly non-malleable, any increase in capacity will remain in the fishery for a long period of time giving rise to a prolonged period of excess capacity. While measures designed to address excess capacity in fisheries should focus on containing race behaviours, our analysis indicates that the malleability of capital is also an important determinant of the duration and amount of excess capacity. Our specification of the malleability of capital has been in terms of the rate of depreciation, however the ease with which capital can be transferred between fisheries and also between fishing and non-fishing applications is also an important source of adjustability in the capital stock. The relationship between these factors and the malleability of the capital stock is complex (Salayo et al., 2008, Grafton et al., 1996), and better understanding this relationship is an important area for future research. In addition, the analysis of environmental variation in this essay has been undertaken in a deterministic model by analysing pre-determined fluctuations in recruitment, and a second useful avenue for further research may be to extend our analysis to a stochastic specification of recruitment.

Appendix: The capacity utilisation ratio ϕ_t

This appendix sets out the derivation of the values of ϕ_t shown in Equation (3.8) of the main body of this essay, given the definition of $\bar{\mu}_t$ shown in Equation (3.4). The capacity utilisation ratio ϕ_t is bounded above and below by 1 and 0, respectively, so that it takes the form:

$$\phi_t = \min(1, \hat{\phi}_t) \quad (\text{A.1})$$

where $\hat{\phi}_t$ represents the point of simultaneous stability in the biological and economic systems (i.e. where the net revenue from harvesting has been exhausted) and occurs where the expected net present value of a unit of investment $\bar{\mu}_t$ is equal to zero. Given the definition of $\bar{\mu}_t$ from Equation (3.4) and the condition from the Gordon-Schaefer model that $h_t = z_t \cdot G(x_t) = z_t \cdot r x_t (1 - x_t / \bar{x})$, i.e. the harvest during any period is equal to the recruitment of the fish population during that time, the derivation of $\hat{\phi}_t$ is shown below in steps (A.2)-(A.5):

$$\bar{\mu}_t = \frac{(pqx_t - c)\phi_t}{\gamma + \delta} = \frac{pq\bar{x}\phi_t \left(1 - \frac{qK_t}{z_t r} \cdot \phi_t\right) - c\phi_t}{\gamma + \delta} = 0, \quad z_t > 0 \text{ and } K_t > 0 \quad (\text{A.2})$$

$$\frac{pq^2\bar{x}K_t}{z_t r}.\phi_t^2 - (pq\bar{x} - c)\phi_t = 0, \quad z_t > 0 \text{ and } K_t > 0 \quad (\text{A.3})$$

$$\frac{pq^2\bar{x}K_t}{z_t r}.\phi_t = (pq\bar{x} - c), \quad z_t > 0, K_t > 0 \text{ and } \phi_t > 0 \quad (\text{A.4})$$

$$\phi_t = \frac{z_t r (pq\bar{x} - c)}{pq^2\bar{x}K_t}, \quad z_t > 0, K_t > 0 \text{ and } \phi_t > 0 \quad (\text{A.5})$$

From step (A.5) it is clear that $\hat{\phi}_t = 1$ when $z_t = \frac{pq^2\bar{x}K_t}{r(pq\bar{x} - c)}$, so that the analytical expression

for ϕ_t , as shown at Equation (3.8) of the main text, is:

$$\phi_t = \begin{cases} 1 & z_t \geq \frac{pq^2\bar{x}K_t}{r.(pq\bar{x} - c)} \\ \frac{z_t.r.(pq\bar{x} - c)}{pq^2\bar{x}K_t} & 0 < z_t < \frac{pq^2\bar{x}K_t}{r.(pq\bar{x} - c)} \end{cases}, \quad K_t > 0 \quad (\text{A.6})$$

Chapter 4. Excess Capacity and Efficiency in the Post-ITQ Fishery: The Case of the Tasmanian Rock Lobster Fishery

4.1 Introduction

Controlling the emergence of new, and managing existing, fishing capacity is of major concern to fisheries regulators and policymakers worldwide (OECD, 2009, FAO, 2008, FAO, 1999, Pomeroy, 2012). Fishing capacity refers to the technical ability of a vessel or fishing fleet to harvest fish, under normal or customary operating conditions (Pascoe et al., 2003, Kirkley and Squires, 1999, Johansen, 1968). In terms of the overall fishery, excess capacity occurs when the fishing capacity exceeds the level of harvest that is observed from the fishing fleet, and this represents ‘pure’ economic waste in the sense that the total harvest could have been taken with a smaller or less technically advanced fishing fleet (Salayo et al., 2008, Clark and Munro, 2002, Gréboval and Munro, 1999). Such waste not only raises the potential for the spill-over of fishing effort between fisheries, but also signals opportunities for the improvement of the fishery’s performance.

The development of excess capacity is well understood in fisheries where there are incentives for race to fish and race to invest behaviour by the fishery’s participants. For example, excess capacity is a long standing issue in limited entry fisheries, where it arises through a process termed ‘capital stuffing.’ Capital stuffing describes the gradual increase in fishing capacity that occurs in limited entry fisheries as fishers invest in better gear and larger vessels in order

to gain greater harvests from the fishery (Townsend, 1985). In fisheries where a manager attempts to control the global harvest by restricting the season length (Homans and Wilen, 1997), excess capacity arises as fishers compete for a greater share of the manager's target harvest (Munro and Clark, 2003). In unregulated fisheries, where the incentives for such race behaviour are all-pervasive, the analysis in the first two essays of this thesis has shown how the non-malleability of capital and environmental variation, both of which are common features of world fisheries, contribute to the development of excess capacity.

It is commonly argued that the implementation of an ITQ system can eliminate the race to fish and improve both biological and economic outcomes for the fishery (Grafton et al., 2006, Costello et al., 2008, Branch, 2009). An ITQ system firstly establishes a Total Allowable Catch (TAC) control that limits the fishery's harvest, and then creates a set number of transferable rights to the TAC that can be traded between the fishery's participants. Although contentious in the literature, it is often argued that the trade in these rights will encourage the transfer of fishing effort from less efficient to more efficient fishers (Österblom et al., 2011, Grafton, 1996, McCay, 1996). The reduction in vessel numbers that occurs as the less efficient fishers are excluded from the fishery also has the potential to reduce or eliminate levels of excess capacity. Since the total harvest of the fishery is shared among fewer vessels, the production of the most efficient vessels may approach their fishing capacity and thereby reduce excess capacity. The reduction in vessel numbers, and therefore the decline in excess capacity, can occur quickly, or may be drawn out over a number of years, depending on the availability of alternatives for the incumbent fishers (Grafton et al., 1996, Squires and Kirkley, 1991, Vestergaard et al., 2005).

The success of ITQ systems at eliminating the race to fish depends on a number of specific factors, which include effective governance (Hanna, 1999); a strong monitoring, control and surveillance system (Parslow, 2010); and critically on implementing a binding TAC constraint (Kompas et al., 2009, Grafton et al., 2007, Kompas and Gooday, 2007). When the TAC is non-binding, the fishery can revert to a regulated open access or limited entry paradigm (Emery et al., 2014, Kompas et al., 2009, Grafton et al., 2007, Kompas and Gooday, 2007) in which the incentives for race behaviour are well known and lead to an increase in fishing effort (Emery et al., 2014, Kompas et al., 2009). Periods of non-binding TAC have been observed in the northern zone of the South Australian rock lobster fishery (Linnane et al., 2010, McWhinnie and Otumawu-Apreku, 2013), the Australian south eastern trawl fishery (Elliston et al., 2004, Kompas and Gooday, 2007), and also in the Tasmanian rock lobster fishery (Emery et al., 2014). Studies of these fisheries overwhelmingly find an increase in fishing effort due to the non-binding TAC and, in some cases, a decline in the total value of the harvest (Elliston et al., 2004, Kompas and Gooday, 2007).

In the Tasmanian rock lobster fishery, Emery et al. (2014) find a period of non-binding TAC is associated with an increase in the temporal concentration of fishing effort (i.e. pot lifts), and also observe a drop in the lease price of quota over this period. There are many non-fishing quota owners in this fishery who lease units at the prevailing market price to ‘rental’ fishers that harvest from the resource (van Putten et al., 2011, van Putten and Gardner, 2010). When the TAC is non-binding, the drop in the rental price of quota allows the re-entry of latent vessels (Emery et al., 2014) that are operated by fishers who cannot harvest or harvest as much at the market clearing prices. Using the Adjusted Gini coefficient and the Normalised Herfindahl-Hirschman Index, Emery et al. (2014) find a concentration of fishing effort in the first two weeks of November in quota years where the TAC was non-binding. In

this essay, we investigate the same quota years for evidence of race behaviour in the fishery by directly examining the levels of excess capacity and efficiency in the fishery over this period.

In general, a small number of studies have compared excess capacity before and after the introduction of an ITQ system. These studies tend to find evidence of only a small reduction in excess capacity following the introduction of such systems (Dupont et al., 2002, Solís et al., 2014b), although some studies do find a more significant change in capacity utilisation. For instance, Squires et al. (2010) investigate excess capacity before and after the introduction of an ITQ system, and find evidence to support the ability of such systems to deliver reductions in excess capacity over a longer time period. To the best of our knowledge, however, there has been no study that directly investigates the temporal (i.e. dynamic) behaviour of excess capacity and efficiency in a post-ITQ fishery; nor is there any economic investigation of changes in excess capacity and efficiency during a period of non-binding TAC in such a fishery.

In this essay, we use a census of compulsory logbook data for the Tasmanian rock lobster fishery (an Australian fishery) from January 2000 to December 2013 to derive empirical estimates of excess capacity and efficiency in that fishery over time. The Tasmanian rock lobster fishery has been ITQ-managed since the 1998 quota year (Hartmann et al., 2013), and from the 2008 to the 2010 quota years the TAC in the rock lobster fishery was non-binding (Emery et al., 2014, Hartmann et al., 2013). We derive estimates of excess capacity and efficiency in the fishery for the 2000 to the 2013 quota years using the Data Envelopment Analysis (DEA) method. In this essay we define excess capacity as occurring when the unbiased capacity utilisation ratio is less than one. The unbiased capacity utilisation

ratio removes a bias that is present in conventional capacity utilisation measures by accounting for differences in technical efficiency that occur between vessels (Kirkley et al., 2002). Our empirical estimates enable us to explore the relationship between excess capacity and the race for fish by investigating whether the adjustment of the fishery continues over a long period of time after the lessening of race behaviour following the introduction of the ITQ, which may indicate that the ITQ system has a larger effect on excess capacity than is suggested by most previous empirical studies; and whether the re-emergence of race to fish behaviour during a period of non-binding TAC in the fishery can be observed in the pattern of excess capacity and efficiency.

4.2 Methods

4.2.1 Defining and measuring capacity utilisation and technical efficiency

In fisheries, capacity utilisation represents the proportion of a vessel's capacity output that is utilised to produce the current level of output. The commonly accepted definition of capacity output is the maximum output that can be produced in a period of time, given normal or customary operating conditions, with existing plant and equipment and provided that the availability of variable factors is not restricted. Färe et al. (1989) define capacity utilisation as the ratio of the individual vessel's actual output to the capacity output; however inefficiencies that are inherent to the usual operating conditions in the fishery may bias this measure. An unbiased measure of capacity utilisation can be estimated by calculating the ratio of the vessel's technically efficient output to its capacity output (Kirkley et al., 2002). Technically efficient output refers to the maximum output that can be obtained from a given set of inputs when output is constrained by the availability of both the fixed and variable inputs. These

definitions of capacity utilisation, capacity output, and technically efficient output accord with the recommendations of the 1998 Technical Consultation on the Measurement of Fishing Capacity held by the Food and Agriculture Organization of the United Nations (FAO) and have been widely adopted by empirical analyses of excess capacity in fisheries (Dupont et al., 2002, Squires et al., 2010, Kirkley et al., 2002).

We measure technically efficient and capacity output using the output orientated DEA approach. This method searches the available production data for convex combinations that generate the greatest output for a given level of fixed inputs (in the case of capacity output) or both fixed and variable inputs (in the case of technically efficient output). The alternative to measuring technically efficient and capacity output is termed input orientated DEA, and this method searches the production data for combinations of the data points that minimise the use of inputs for a given level of output. A practical issue arises with this approach in the case of capacity measurement, where the fixed inputs of the fishery are assumed to be static at the vessel level. The use of output-orientated DEA is more practical for capacity measurement, but also has the limitation that it assumes the output of individual vessels can be expanded for a given the set of vessel inputs (and this may not be the case for quota managed fisheries, where catch is controlled).

4.2.1.1 Estimating capacity output

Färe et al. (1989) distinguish between fixed and variable inputs, and measure the level of capacity output by assuming that the utilisation of variable inputs can be adjusted but that production is constrained by the availability of the fixed inputs. Consider observations for vessels $j = 1 \dots J$ in a fishery producing output $Y^j \in R_+$ by using a vector of $n = 1 \dots N$ inputs $X^j \in R_+^N$. We make standard assumptions in relation to inputs and outputs, so that: the level

of production $Y^j > 0$ for all j (i.e. every vessel in the fishery has undertaken some fishing activity); that $\sum_j X_n^j > 0$ for each input n (i.e. each input is used by at least one vessel); and also $\sum_n X_n^j > 0$ for all vessels j (i.e. each vessel uses at least one input).

Under these standard assumptions, Färe et al. (1989) show that capacity output can be formalised as the solution to the Linear Optimisation Problem below:

$$\max_{\theta_1, z, \lambda} \theta_1 \quad (4.1)$$

subject to:

$$\theta_1 Y^j \leq \sum_j z^j Y^j \quad (4.1.1)$$

$$\sum_j z^j X_n^j \leq X_n^j, \quad n \in \mathbf{K} \quad (4.1.2)$$

$$\sum_j z^j X_n^j = \lambda_n^j X_n^j, \quad n \in \mathbf{V} \quad (4.1.3)$$

$$\sum_j z^j = 1 \quad (4.1.4)$$

where $1/\theta_1$ is an output-oriented measure of *biased* capacity utilisation, and this value is bounded between 0 and 1 (since $\theta_1 \geq 1$). The vector \mathbf{V} represents the set of variable inputs to the production process, and the vector \mathbf{K} identifies the elements of n which relate to fixed inputs of production. The intensity variables $z^j \geq 0$ for each vessel serve to construct the

production technology from convex combinations of the observed data points. The optimality conditions on these linear combinations of the production points are imposed by Constraints (4.1.1) and (4.1.2). Taken together, these constraints require the optimising algorithm to choose between members of the convex hull¹ which use less fixed inputs than the current vessel (i.e. $\sum_j z^j X_n^j \leq X_n^j, n \in K$) and which produce at least a factor θ_1 times more output (i.e. $\theta_1 Y^j \leq \sum_j z^j Y^j$). Constraint (4.1.3) requires the full utilisation of variable inputs with the j^{th} vessel's utilisation of the n^{th} variable input $\lambda_n^j \geq 0$ for all $n \in V$. Constraint (4.1.4) is included in the optimisation problem when the production technology exhibits variable returns to scale (Färe et al., 1989, Grosskopf, 1986). The capacity output for the vessel j is obtained by multiplying the variable θ_1 by the vessel's observed output Y^j , which is to say that we refer to the product $\theta_1^j Y^j$ is the capacity output for vessel j .

4.2.1.2 Estimating technically efficient output and technical efficiency

The technically efficient level of output is the maximum observed level of output that is attained from a given set of inputs (Farrell, 1957, Coelli et al., 2005). Such technically efficient output can be measured from the Linear Optimisation Problem below:

¹ The convex hull is the topologically smallest convex set that contains the production data.

$$\max_{\theta_2, z} \theta_2 \quad (4.2)$$

subject to:

$$\theta_2 Y^j \leq \sum_j z^j Y^j \quad (4.2.1)$$

$$\sum_j z^j X_n^j \leq X_n^j, n \in K \cup V \quad (4.2.2)$$

$$\sum_j z^j = 1 \quad (4.2.3)$$

where all variables are as defined previously, $\theta_2 \geq 1$, and $1/\theta_2 \in [0,1]$ is the output-orientated measure of the technical efficiency of vessel j , when production is constrained by the availability of both the fixed and variable inputs. As in the case of capacity output, Constraints (4.2.1) and (4.2.2) above impose the optimality conditions on the combination of production points given by the intensity variables z^j and Constraint (4.2.3) is required because of the possibility of variable returns to scale in the fishery's production technology. The technically efficient output for the vessel j is calculated by multiplying the variable θ_2 for that vessel by its observed output Y^j , which is to say, we refer to the product $\theta_2^j Y^j$ as the technically efficient output for vessel j .

4.2.1.3 Estimating unbiased capacity utilisation

Calculation of unbiased capacity utilisation for the vessel j during the year t , CU_t^j , is as shown below:

$$CU_t^j = \frac{\theta_{2,t}^j Y_t^j}{\theta_{1,t}^j Y_t^j} \quad (4.3)$$

where $\theta_{1,t}^j$ is the value of θ_1 obtained from solving the Linear Optimisation Problem (4.1) for vessel j using the production data for year t ; and $\theta_{2,t}^j$ is the value of θ_2 obtained from the Linear Optimisation Problem (4.2) for vessel j similarly using production data for year t . The variable Y_t^j is the observed output of vessel j in year t .

4.2.2 Estimating scale efficiency

Scale efficiency is a measure of efficiency loss that occurs due to a deviation from the technically optimal production scale for a variable returns to scale production technology (Coelli et al., 2005). Scale efficiency is typically measured as the distance between the technically efficient production point along the variable returns to scale (VRS) production frontier and the technically optimum production scale on the constant returns to scale (CRS) frontier (Balk, 2001, Iliyasu et al., 2014, Coelli et al., 2005, Favero and Papi, 1995). The CRS production technology represents a boundary of the linear span of the production points over R^+ and is defined by the most productive points in the dataset. The vertical distance between the CRS and the VRS technologies represents the amount of output that is foregone due to the lower productivity at the current scale of operation (Coelli et al., 2005). The scale efficiency of the j^{th} vessel during the year t , SE_t^j , is shown below:

$$SE_t^j = \frac{\theta_{2,t}^j Y_t^j}{\theta_{2,t}^{CRS,j} Y_t^j} \quad (4.4)$$

where $\theta_{2,t}^j$ is the value of θ_2 obtained from the Linear Optimisation Problem (4.2) for vessel j using production data from year t ; and $\theta_{2,t}^{CRS,j}$ is the similarly obtained value for a CRS production technology. The CRS production technology is introduced to the Linear Optimisation Problem (4.2) by omitting Constraint (4.2.3), i.e. $\sum_j z^j = 1$.

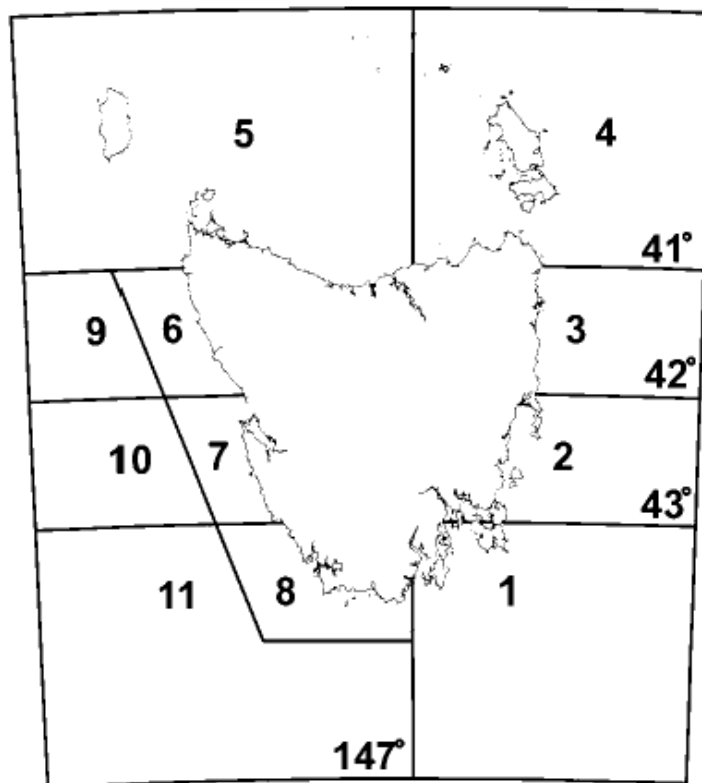
4.3 The Tasmanian rock lobster fishery and data

4.3.1 The Tasmanian rock lobster fishery

Fishing for southern rock lobster (*Jasus Edwardsii*) occurs in Tasmanian state waters, which encompass that part of the Exclusive Economic Zone up to three nautical miles from the coast of the Tasmania. Management of the Tasmanian rock lobster fishery occurs through a combination of both input and output controls. Entry to the fishery is limited by a licencing regime. In the 2013-14 fishing season there were 312 licenced operators (DPIPWE, 2015), however not all of these operators were active harvesters in the fishery. On average from the 2009-10 fishing season to the 2011-12 fishing season there were 234 active vessels in the fishery (Hartmann et al., 2013). The commercial fishing season for the rock lobster runs from March to February each year, with a closure in place for the majority of the state in September, and for the whole state during October. The rock lobster fishery has been subject to an ITQ system, supplemented by size limits and gear restrictions, since the beginning of the 1998 quota year (Gardner, 2012). The gear limit was raised from 40 to 50 pots per vessel at the time the ITQ system was introduced. To account for geographical variation in the

fishery, a single TAC² for the commercial fishery is set each year using a spatially-explicit model that divides the fishery into the eleven stock assessment areas shown below.

Figure 4.1: Schematic boundaries of the stock assessment areas for the Tasmanian rock lobster fishery (adapted from Hartmann et al., 2013)



² Very recently, the introduction of an ‘east coast cap’ in the fishery has meant there is a separate catch control for the rock lobster populations along the east coast of Tasmania. For the period of the fishery investigated in this essay, however, there was no east coast cap, and therefore just a single TAC for the fishery.

Recruitment in the fishery primarily occurs through the settlement of larvae from the water column (Gardner, 2012), and is therefore unevenly distributed around the state. The recruitment to a particular area of the fishery depends on the ocean currents and the survival of the larvae. The productivity of the fishery also varies by region. In the 2011-12 fishing season (Hartmann et al., 2013) the stock assessment areas on the east coast (i.e. 1 to 4) attracted 39.3 percent of the total pot lifts. Stock assessment area 5, which surrounds King Island, attracted 22.5 percent of the total pot lifts; and the remaining stock assessments areas (i.e. 6 to 11), which are on the west coast, attracted 38.1 percent of the total pot lifts. In the same fishing season the west coast stock assessment areas were responsible for 45.2 percent of the total production of the fishery. Those on the east coast recorded 28.7 percent of the production and the stock assessment area surrounding King Island was responsible for 26.1 percent.

The fishery is harvested by both quota owners and lease fishers, who rent quota units in order to harvest from the fishery. All fishers must hold at least one quota unit in order to maintain their fishing licence, and need a minimum of fifteen units to go fishing. For lease fishers, the remaining fourteen units can be obtained from a decentralised market for quota (van Putten et al., 2011). Quota owners are not required to fish, and since the beginning of the system there has been a growing trend towards a fishery that is characterised by lease fishers who are supplied by a group of non-fishing quota investors (van Putten et al., 2011, van Putten and Gardner, 2010). Vessels in the Tasmanian rock lobster fishery do not participate in any significant way in any other fisheries, which suggests that the malleability of capital may be low in this fishery.

4.3.2 Fishery data

The variables used for the analysis presented in this essay are shown in Table 4.1. The BIOMASS variable was obtained from data provided by the Institute for Marine and Antarctic Studies. The remaining variables (VESS_ID, AREA, YEAR, MONTH, CREW, POTLIFTS, WEIGHT and OVERALL_LENGTH) were obtained from a database of daily log-book records for the Tasmanian rock lobster fishery that is maintained by the Tasmanian Department of Primary Industries, Parks, Water and the Environment. These log-book records represent a regular census of the fishery, and the log-book data have been made available for this study as monthly aggregates within the 2000 to 2013 fishing seasons.³

Table 4.1: Definition of variables

Variable name	Description
VESS_ID	Vessel identification number in the dataset
AREA	Stock assessment area (1 to 11)
YEAR	Calendar year to which the catch relates
MONTH	Calendar month to which the catch relates
CREW	Number of crew on-board the vessel for the catch observation, including the skipper
BIOMASS	Rock lobster biomass from the stock assessment area to which the harvesting related (in tonnes)
POTLIFTS	Total number of pots lifted from the ocean during the month
WEIGHT	Weight of the rock lobster caught in the month (in tonnes)
OVERALL_LENGTH	Overall length of the vessel (in meters)

³ Log books have been collected for earlier years of the fishery, however the data was not made available for the study in this essay.

While the majority of the variables in Table 4.1 were available for each month of the quota year from March to February, BIOMASS was recorded only on a seasonal basis. Consequently VESS_ID was used to aggregate the monthly observations of other variables within each quota year by fishing vessels. Prior to this aggregation the monthly vessel data were cleaned. Missing POTLIFTS records were filled using the most recent state-wide average pot lifts per unit of catch (Hartmann et al., 2013), and in one case a missing WEIGHT observation was replaced with a zero.⁴ The missing OVERALL_LENGTH observations were populated with the average value for the remainder of the dataset. CREW observations in excess of 12 members were also excluded, given the maximum length of a fishing vessel in the data (i.e. 29 meters), and the average number of crew per meter of length was used to assign the crew numbers to observations with positive fishing activity that recorded zero crew members. Of the remaining observations, those with missing values and those with a catch in excess of 6 kg per pot were also excluded (Gary Carlos, per. comm.). The monthly data were aggregated by vessel and quota year. This means that POTLIFTS represents the total number of pots lifted by a vessel during a quota year and WEIGHT represents the total weight of lobsters caught by that vessel during the quota year. The BIOMASS, OVERALL_LENGTH and CREW variables represent the average inputs for the vessel during the quota year. After aggregation and cleaning, the dataset consisted of 3120 observations. The mean and standard deviation of the variables are reported below in Table 4.2.

⁴ Since the POTLIFTS variable associated with this observation was also zero.

Table 4.2: Summary statistics for the dataset

Variable	Mean	Standard	Type of
CREW	1.79	0.58	Variable Input
POTLIFTS	6118.70	3234.00	Variable Input
WEIGHT	6.14	4.13	Output
OVERALL_LENGTH	14.27	2.85	Fixed Input
BIOMASS	442.40	185.50	Fixed Input

Table 4.2 shows that, for the entire period from the 2000 to the 2013 quota years, the average length of a vessel in the Tasmanian rock lobster fishery is approximately 14 meters. This vessel is generally operated by one or two crew members (i.e. the skipper and a deck hand), lifts a total of 6118 pots during a quota year and harvests approximately 6.14 tonnes of lobsters. Given the areas in which the vessel operates, and the amount of fishing it does in each area, the average biomass input to production is 442.40 tonnes. These statistics account for variation between vessels within each quota year as well as across time, i.e. from one quota year to the next, and therefore represent the average vessel that has harvested the fishery from the 2000 quota year to the 2013 quota year.

The fourth column in Table 4.2 identifies each of the variables as being a fixed input, a variable input or an output. The distinction between fixed and variable inputs is based on the ease with which they can be adjusted. Following Dupont et al. (2002) we classify the OVERALL_LENGTH of the vessel as a fixed input, represents the capital input to production. We also classify BIOMASS as a fixed input since it is largely out of the control

of the individual operators.⁵ The remaining variables CREW and POTLIFTS are variable inputs as these can be adjusted by the individual operators within a fishing season. The variable WEIGHT records the weight of the harvest of each vessel during each season, and represents the output of the production process.

4.4 Results

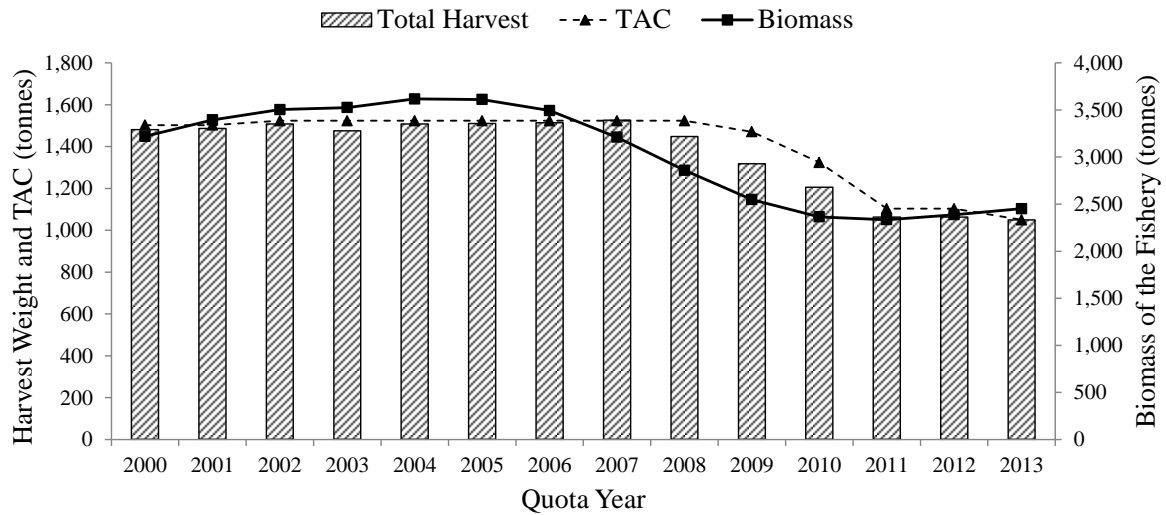
4.4.1 TAC, harvest and the number of vessels

The overarching aim of this essay is to investigate changes in excess capacity and efficiency in a post-ITQ period of the Tasmanian rock lobster fishery, and also whether the re-mergence of race behaviour can be observed in the excess capacity and efficiency scores when the TAC in that fishery is non-binding. To understand changes in the fishery over the study period we first report the total harvest, the average harvest, the biomass, the TAC and the number of active vessels in the fishery, and these are shown in Panels (a) and (b) of Figure 4.2 below.

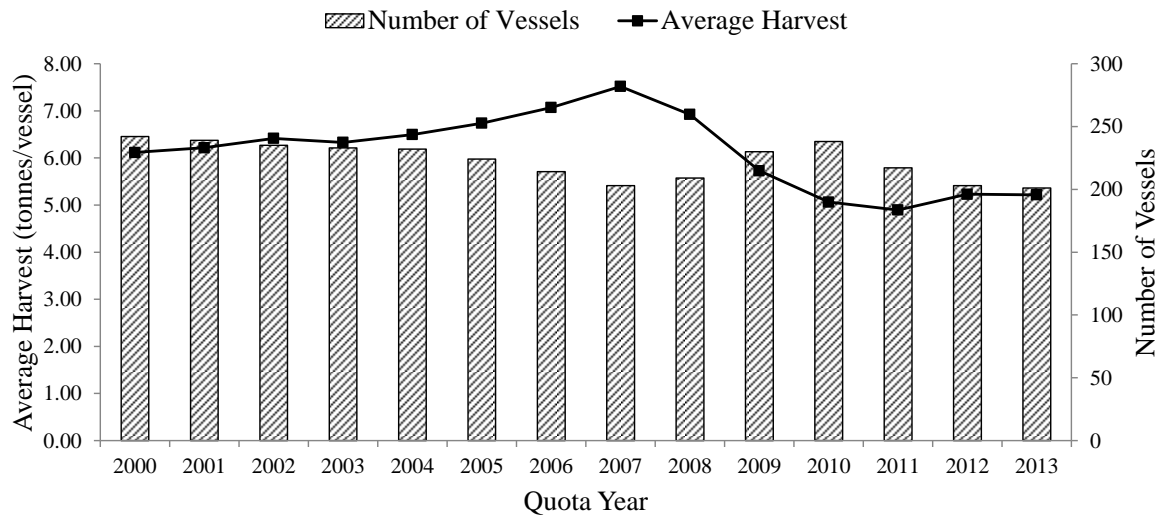
⁵ As described in section 4.3.1, there is some spatial variation in this fixed input and the vessel is able to move to different areas of the fishery. This means that vessels have some control over the biological input to production. However this is only possible in any given quota year within the bounds of the available concentrations of rock lobsters, and so we represent this variable as a fixed input.

Figure 4.2: The Tasmanian rock lobster fishery over the 2000 to 2013 quota years

(a) Total harvest, TAC and the biomass of the fishery



(b) The number of vessels and the average harvest of each vessel



Panel (a) of Figure 4.2 shows the evolution of the biomass, harvest and TAC in the fishery. These three variables follow similar patterns over the study period, with the total biomass building steadily until around the 2005 quota year, where it begins to decline. This decline in the biomass eventually leads to reductions in the total harvest of the fishery, starting in the 2008 quota year, and also in the TAC of the fishery beginning in the 2009 quota year. The biomass, harvest and TAC all stabilise in the 2011 quota year, and end the study period at 76.2, 70.8, and 69.9 percent of their levels in the 2000 quota year respectively. Panel (a) also illustrates a period of non-binding TAC between the 2008 and 2010 quota years. During this time the proportion of TAC harvested by the fishery ranged between 89.6 and 95.0 percent. The total harvest of the fishery also declined from the 2008 to the 2010 quota years.

Panel (b) of Figure 4.2 shows the number of vessels participating in the fishery and the average harvest per vessel. During the first eight years of the study period, from the 2000 quota year to the 2007 quota year, the number of vessels operating in the fishery declined from 242 to 203 and the average harvest increased from 6.1 to 7.5 tons. This trend of decreasing participation in the fishery was reversed in the 2008 quota year when the TAC became non-binding, and a substantial drop in the price of quota encouraged latent vessels to re-enter the fishery (Emery et al., 2014). From the 2007 to the 2011 quota years the average harvest per vessel fell by 34.9 percent, and vessel numbers increased to near the level recorded in the 2000 quota year. By the 2013 quota year, the number of vessels had declined again to a low of 201 vessels (close to the level recorded in the 2007 quota year). The average harvest per vessel remained at about 5.0 tonnes or just 14.7 percent lower than at the beginning of the study period. It is also worth noting that, in the four years preceding the introduction of the ITQ system in 1998, there was an average of 334 vessels that actively harvested in the fishery (Hartmann et al., 2013). Directly after the introduction of the ITQ

system, this number of active vessels dropped to 286, and the decline continued throughout the 1999 and 2000 quota years. In terms of vessel numbers, therefore, the fishery's adjustment occurred mostly from the 1998 to the 2000 quota years, which immediately followed the introduction of the ITQ system, and which do not form part of the study period for this essay.

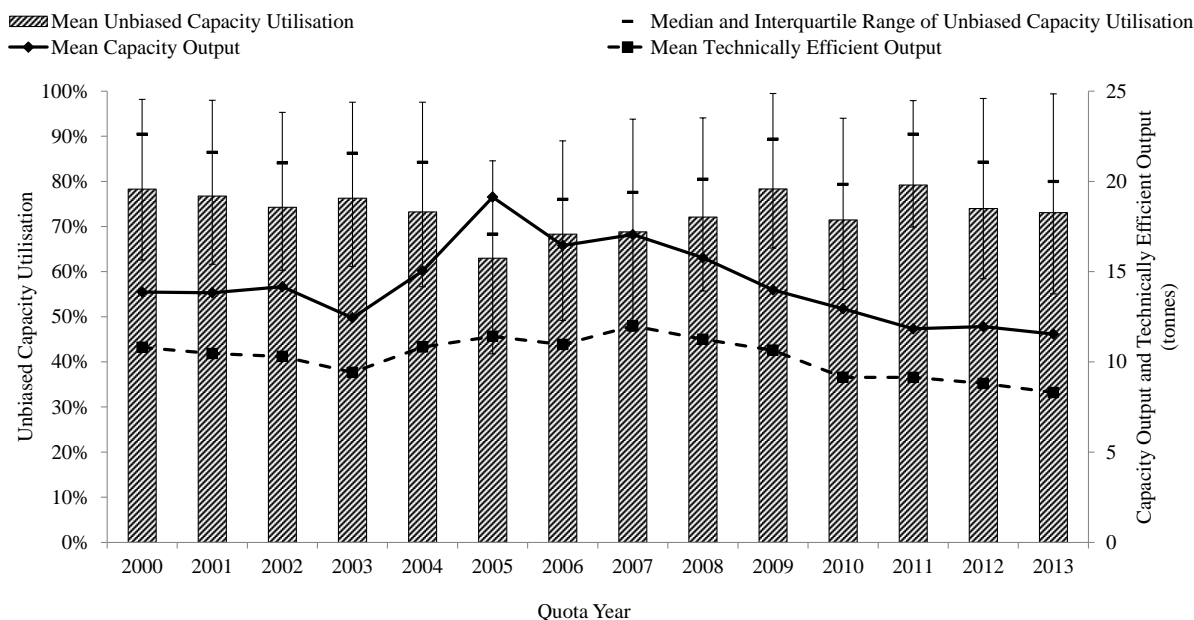
4.4.2 Capacity utilisation and efficiency in the fishery

4.4.2.1 Unbiased capacity utilisation, technical efficiency and scale efficiency

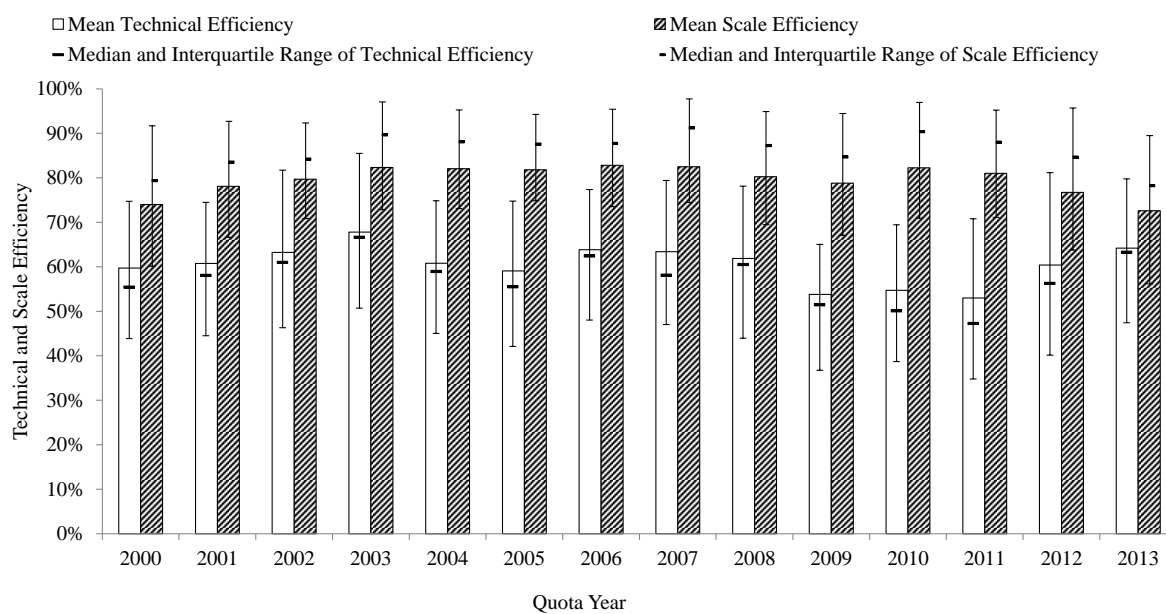
One of the main aims of this essay is to explore the evolution of excess capacity and efficiency in the Tasmanian rock lobster fishery over a period following the implementation of an ITQ system. We do this by observing and analysing the behaviour of the mean, median and interquartile range of unbiased capacity utilisation, shown in Panel (a) of Figure 4.3, and the same measures for technical and scale efficiency, shown in Panel (b) of Figure 4.3. The capacity output and technically efficient output are also reported in Panel (a) of Figure 4.3.

Figure 4.3: Unbiased capacity utilisation, technical efficiency and scale efficiency

(a) Unbiased capacity utilisation



(b) Output-orientated technical and scale efficiency



As shown in Panel (a) of Figure 4.3, capacity utilisation in the fishery remained above 60.0 percent for the entire study period. The mean capacity utilisation was 78.0 percent in the 2000 quota year, and about 73.0 percent in the 2013 quota year. The mean capacity utilisation over the entire period was approximately 73.0 percent. These high levels of capacity utilisation indicate the most efficient vessels in the fishery cannot significantly increase their output by increasing the use of variable inputs, and point to a low level of economic waste in the fishery after the introduction of the ITQ system. Capacity utilisation has shown some variation over the study period, between a low of 63.0 percent in the 2005 quota year and a high of 79.0 percent in the 2011 quota year. As described in Equation (4.3), our measure of unbiased capacity utilisation represents the ratio of the technically efficient output to the capacity output for an individual vessel. Panel (a) of Figure 4.3 shows movements in the mean values of both these elements, which have declined over the study period by 2.3 and 2.5 thousand tonnes, or 17.0 and 23.0 percent, respectively. This decline has not been monotonic, and in particular there was a spike in capacity output in the 2005 quota year that coincided with a fall in capacity utilisation. A similar spike in technically efficient output was not observed in the 2005 quota year.

Panel (a) of Figure 4.3 also shows that the median capacity utilisation is always greater than the mean capacity utilisation, which suggests the presence of some vessels of very low capacity utilisation in the fishery's data. With the exception of the 2011 quota year, the dispersion (i.e. the interquartile range) of the capacity utilisation remained mostly stable over the study period. In the 2011 quota year, the interquartile range contracted to 28.0 percentage points, compared with an average of 39.1 percentage points for the other quota years. This represents an increase in the homogeneity of the vessels in terms of their capacity utilisation, and possibly reflects a concentration of fishing effort among fewer harvesters. This could

have resulted from a rush to buy quota units when the TAC again became scarce at the beginning of the 2011 quota year. On the whole, our results indicate that the homogeneity of the active vessels in the fishery, with respect to capacity utilisation, has remained stable over the study period. In particular, the dispersion of capacity utilisation is unaffected by the non-binding TAC between the 2008 and the 2010 quota years. This suggests that latent vessels that re-entered the fishery over the period of non-binding TAC have either very low or very high capacity utilisation or represent a very small fraction of the total number of vessels in the fishery.

Panel (b) of Figure 4.3 shows that there were modest changes in technical efficiency over the study period, with mean technical efficiency increasing from 60.0 to 64.0 percent. Mean technical efficiency varied substantially over the study period, ranging from a high of 68.0 percent in the 2003 quota year to a low of 53.0 percent in the 2011 quota year. In particular, the fishery displayed a marked period of low technical efficiency from the 2009 to the 2011 quota years. The scale efficiency of the fishery varied between 73.0 and 83.0 percent over the study period, but remained largely unchanged between the start of the period (when it was 74.0 percent) and the end of the period (when it was 73.0 percent). Both technical efficiency and scale efficiency displayed four years of consecutive increase from the 2000 to 2004 quota years, not long after the introduction of the ITQ system. This may indicate that the fishery was operating at an inefficient scale (i.e. in a region of decreasing returns to scale) with low technical efficiency before the introduction of the ITQ system. Panel (b) of Figure 4.3 also shows that the mean values of scale efficiency were higher than those of technical efficiency throughout the study period. For the 2000 to the 2013 quota years the mean values of technical efficiency and of scale efficiency were around 60.0 and 80.0 percent respectively. This suggests that the fishers were operating at close to the technically optimal production

scale but were not technically efficient over the study period. This would indicate that the productivity of the fishery could be increased by improving the utilisation of variable inputs but not by changing the total use of fixed inputs.

Panel (b) of Figure 4.3 also shows that the mean technical efficiency is consistently above the median technical efficiency, which suggests a number of highly efficient harvesters, possibly who know the better locations or times to fish for rock lobster (Madau et al., 2009). On the other hand, Panel (b) of Figure 4.3 shows that the mean scale efficiency is consistently below the median scale efficiency, which suggests a highly inefficient scale of operation among some vessels. Extreme values of scale inefficiency may reflect fishers who are unable to lease as many units of quota as they desire in the decentralised lease market. Also, the dispersion of scale efficiency appears to be lower at higher median values and higher at lower median values. The Pearson correlation coefficient between the median and the interquartile range of the scale efficiency is -0.7 (and is just 0.04 in the case of technical efficiency). This correlation might reflect differences in production technologies between vessels, so that a change in the fishery's total harvest may have a disproportionately large impact on the scale efficiency of some vessels. Finally, the dispersions of both technical efficiency and scale efficiency do not change markedly during the period of non-binding TAC, from the 2008 to the 2010 quota years. That is to say, the re-entry of latent vessels over this period has not altered the homogeneity of the fleet in terms of its scale or technical efficiency. On the whole, the period of non-binding TAC caused vessels in the fishery to operate at a lower technical efficiency, but with about the same level of scale efficiency. The consistency of the scale efficiency over this period may reflect a per vessel pot limit that has applied in the fishery over the study period.

4.4.2.2 Capacity utilisation and efficiency during the period of non-binding TAC

A second aim of the essay is to investigate whether capacity utilisation and efficiency in the Tasmanian rock lobster fishery declined during the period of non-binding TAC from the 2008 to the 2010 quota years. We do this by first partitioning the fishery's data into three distinct sub-periods, which correspond to the non-binding TAC (2008-2010), the quota years preceding the non-binding TAC (2000-2007) and the quota years following the non-binding TAC (2011-2013). The mean values and standard deviations of capacity utilisation, technical efficiency, and scale efficiency for these sub-periods and are reported in Table 4.3. The proportion of the fishery's TAC that was harvested in each sub-period is also shown in Table 4.3, from which we confirm that the proportion of the TAC harvested in the 2008-2010 sub-period (91.9 percent) was markedly below that observed in the two other sub-periods (98.8 percent and 97.5 percent, respectively).⁶

⁶ Note that, due to a carry-over provision that was in place in the fishery during this time, a component of the uncaught quota in each of these quota years may have been carried over and harvested in the following quota year.

Table 4.3: Mean and standard deviation of capacity utilisation, technical efficiency and scale efficiency before (2000-07), during (2008-10) and after (2011-13) the period of the non-binding TAC

	%TAC Harvested	Unbiased Capacity Utilisation		Output-orientated Technical Efficiency		Output-orientated Scale Efficiency	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
2000-2007	98.8%	0.73	0.27	0.62	0.22	0.80	0.19
2008-2010	91.9%	0.74	0.26	0.57	0.22	0.80	0.19
2011-2013	97.5%	0.76	0.27	0.59	0.24	0.77	0.21

The capacity utilisation increased only slightly over the three sub-periods in Table 4.3, and showed no evidence of decline during the sub-period corresponding to the non-binding TAC. Similarly, the scale efficiency remained unchanged between the first and second sub-periods, also giving no indication of a decline as a result of the non-binding TAC. However, the scale efficiency did fall by three percent in the last sub-period (2011-2013). The mean technical efficiency, in contrast, was around five percent lower in the sub-period corresponding to the non-binding TAC when compared with the two remaining sub-periods. Table 4.3 also shows that the standard deviations of the estimates of capacity utilisation and efficiency remain essentially unchanged over the three sub-periods. This confirms that there is no change in the dispersion of these estimates across the individual fishing vessels between the sub-periods, so that changes in capacity utilisation and efficiency seem to represent simultaneous changes among all vessels in the fishery. Therefore, the technical efficiency of most vessels has declined during the non-binding TAC, maybe with the exception of the harvesters that determine the technically efficient production frontier, and this might reflect the re-activation

of inefficient vessels when latent capital began to re-commence harvesting in the fishery from the 2008 quota year.

To further explore how capacity utilisation and efficiency in the ITQ-managed fishery are affected by the TAC constraint, we calculate the partial correlation of capacity utilisation and the two measures of efficiency in the fishery with the TAC and the proportion of TAC harvested in each quota year. These coefficients are reported in Table 4.4 below. The results show a particularly high correlation between technical efficiency and the proportion of the TAC harvested in each quota year. This is consistent with conventional economic theory, which suggests that when the TAC is binding, so that a high proportion of the TAC is harvested, the ITQ mechanism will ensure that effort is allocated to the most efficient vessels, and thereby increase the mean technical efficiency in the fishery. The next highest correlation is between the scale efficiency and magnitude of the TAC constraint. This suggests that the fishery might on average operate in a region of increasing returns to scale, so that when the total harvest of the fishery increases, through a higher TAC, the scale efficiency also increases. Capacity utilisation is negatively correlated with both TAC and the proportion of TAC that is harvested. This observed negative correlation indicates an increase in the utilisation of capacity among active harvesters when the total harvest of the fishery declines. During a period of non-binding TAC, this could reflect vessels increasing their harvesting activity (i.e. shots per quota year) to take advantage of the low quota prices. Where there is a decrease in a binding TAC, on the other hand, the greater scarcity of the TAC may increase the quota price so that vessel operators take more shots per quota year to maintain profits. Similarly, scale efficiency is weakly negatively correlated with the proportion of the TAC harvested. When the TAC becomes binding, the decision about the scale of fishing is no longer made exclusively by the vessel operators, but is partly set by the fishery's manager. As

a consequence, some fishers may no longer be able to independently determine the scale of their harvesting activities, and the mean scale efficiency of the fishery declines. Finally, technical efficiency is weakly positively correlated with the TAC. This might reflect a disproportionate increase in the harvest of the inefficient vessels as the total harvest of the fishery increases, but may also be down to statistical variation over the study period.

Table 4.4: Partial correlation coefficients of capacity utilisation, technical efficiency and scale efficiency with the TAC and the proportion (%) TAC harvested respectively

	Capacity utilisation	Technical efficiency	Scale efficiency
TAC	-0.23	0.29	0.49
% TAC harvested	-0.31	0.64	-0.19

4.5 Conclusion

This essay has investigated the implications for excess capacity and efficiency from the implementation of an ITQ system. It is commonly anticipated that an effective ITQ will reduce or eliminate excess capacity in the fishery. However, theory offers limited guidance as to the adjustment pathway in capacity required for the reduction in excess capacity to occur. Furthermore, most empirical estimates of capacity utilisation before and immediately after the introduction of an ITQ system indicate only modest reductions in excess capacity (Dupont et al., 2002, Solís et al., 2014b). This essay has measured excess capacity using the unbiased measure of capacity utilisation (Kirkley et al., 2002), and investigated

changes in excess capacity and efficiency over a fourteen year study period in the Tasmanian rock lobster fishery that closely followed the introduction of an ITQ system. The essay has also looked for evidence of the re-emergence of race behaviours in the excess capacity and efficiency scores of the fishery when it reverted to a limited entry open access paradigm under a non-binding TAC (Emery et al., 2014, Kompas et al., 2009, Grafton et al., 2007).

Our results have revealed a consistently high level of capacity utilisation and low level of technical efficiency over the study period. Together these results point to low levels of excess capacity among the most efficient operators in the fishery, but possibly also an opportunity for some vessels to improve their use of variable inputs. The mean technical efficiency of the fishery has ranged between 53.0 and 68.0 percent over the study period, with the grand mean being 60.0 percent for all quota years. Solís et al. (2014a) find technical efficiency scores of 41.0 percent and 57.0 percent for two different classes of fishing vessels in the Gulf of Mexico red snapper fishery, after the introduction of the quota management system in that fishery. In an investigation of the ITQ-managed New Zealand rock lobster fishery, Sharp et al. (2004) find technical efficiency scores ranging from 74.0 percent to 82.0 percent. Scale efficiency remains virtually unchanged over the study period. High levels of scale efficiency suggest that, overall, the rock lobster fishers were operating at a scale of production that was close to the technically optimum production scale. The mean scale efficiency in the Tasmania rock lobster fishery has varied between 73.0 and 83.0 percent over the study period with a grand mean of 80.0 percent for all quota years. These measures of scale efficiency are comparable to other studies of wild catch fisheries. Under controlled access management of the Northern Gulf of Mexico reef fishery, Weninger and Waters (2003) find scale efficiency of 79.0 percent. For the small scale fishing fleet in Sardinia, for example, Madau et al. (2009) find scale efficiency of 90.0 percent. In the case of the Tasmanian rock lobster fishery, a

measured correlation between the TAC and the mean level of scale efficiency over the period of this study reveals a positive relationship that is consistent with increasing returns to scale, suggesting the fishery was close to, but below, the technically optimum production scale.

The composition (i.e. heterogeneity) of the fishing fleet is reflected by the dispersion of capacity utilisation, technical efficiency and scale efficiency, which we find have remained mostly unchanged over the study period. The skew of the distribution of technical efficiency, as indicated by the difference between the mean and median values, suggests the presence of outlying vessels with particularly high levels of technical efficiency. This could point to differences in the knowledge of the fishery, i.e. some operators knowing better times or places to harvest rock lobster and therefore are able to achieve a higher technical efficiency than other operators. In the case of the scale efficiency, the same measure of skew suggests a highly inefficient scale of operation among some vessels, which may reflect differences in the production technologies across vessels or point to some fishers being unable to source quota in the decentralised market. Our results reveal a negative correlation between the dispersion and the median value of scale efficiency which suggests changes in the fishery's total harvest have a larger impact on the scale efficiency of some vessels over others. Lastly, the skew of capacity utilisation over the study period indicates the presence of a number of vessels of extremely low capacity utilisation, and this may reflect the suitability of different sized vessels to the general environmental conditions of the fishery (i.e. weather, sea, location of lobsters, etc.).

The analysis in this essay has shown that the increase in excess capacity over time, following the introduction of an ITQ system in the Tasmanian rock lobster fishery, is limited. This essay has found weak evidence that the adjustment of the fishery occurs over a prolonged

time period following the introduction of an ITQ system. A period of increasing scale and technical efficiency from the 2000 to the 2004 quota years could indicate a delayed or prolonged adjustment of the fishery after the introduction of the ITQ system in 1998. A prolonged period of adjustment is also evidenced by a steady decline in vessel numbers up to the 2007 quota year, after which the TAC became non-binding. However, no evidence is found for a marked change in capacity utilisation over the study period. We also do not find any indication of an increase in excess capacity (i.e. a reduction in capacity utilisation) when race to fish behaviour re-emerged in the fishery from the 2008 to the 2010 quota years.

An important caveat to our research is that data from the stock assessment reports for the Tasmanian rock lobster fishery (Hartmann et al., 2013) indicate that most of the change in vessel numbers as a result of the ITQ system seems to have occurred immediately following the introduction of that system (i.e. from the 1998 to the 2000 quota years). While there is limited evidence in other studies for reductions in excess capacity in the years immediately following the introduction of the ITQ system (Solís et al., 2014b, Dupont et al., 2002), a data limitation in this essay has meant that our analysis has been unable to establish whether this is the case for the Tasmanian rock lobster fishery. Dupont et al. (2002) measure capacity utilisation before and after the introduction of an ITQ system in the multispecies Scotia-Fundy mobile gear fishery. After the introduction of the ITQ system in the 1991 fishing season they find the mean capacity utilisation of 65.3 percent, compared with 64.9 percent in the 1990 fishing season, just prior to the introduction of the system. For the Gulf of Mexico red snapper fishery, Solís et al. (2014b) measure mean capacity utilisation before and after the introduction of an ITQ system of 21.1 percent and 22.5 percent respectively. Similar changes may occur in the Tasmanian rock lobster fishery, but this is yet to be established, and

an investigation of the behaviour of the fishery in the quota years immediately preceding and following the 1998 quota year is an important area for further research.

ITQ systems have become an increasingly commonplace regulation in world fisheries. While reducing vessel numbers, we have found that the effect of such a system on excess capacity has been negligible over the period of this study. In particular, our analysis has revealed that a period of non-binding TAC in the Tasmanian rock lobster fishery, over which evidence of the well-known race to fish has been observed (Emery et al., 2014), was not associated with an increase in excess capacity. The latent capital that re-commenced harvesting during this period did not significantly alter the ratio of the technically efficient output (i.e. the output of the technically efficient vessel) to the capacity output of the vessels in each category of overall length. As a consequence the mean level of unbiased capacity utilisation did not change markedly. Finally, it is not clear whether the measured levels of capacity utilisation in the Tasmanian rock lobster fishery represent wasteful excess capacity or economically efficient excess capacity (i.e. capacity that is maintained by fishers to take advantage of the spatial and temporal heterogeneity of the resource). Such 'efficient' excess capacity has been demonstrated in the case of a sole-owner fishery with stochastic fluctuations in recruitment by Poudel et al. (2013). Since capacity utilisation in the Tasmanian rock lobster fishery did not substantially change during a period of non-binding TAC, when the race to fish re-emerged in the fishery, it is possible that the underutilisation of capacity that is measured in the fishery represents some efficient level. However, it is also possible that a combination of the licence limitation and the per vessel pot limit that applied over the study period have limited the expansion of capacity during the non-binding TAC to that caused by the re-entry of latent vessels, and therefore prohibited further wasteful excess capacity from appearing in the fishery over that period.

Finally, the catchability of lobsters in the Tasmanian rock lobster fishery can change dramatically within quota years, both by location and time of year, and also between quota years of the fishery. Some of the variation in the excess capacity and efficiency over the study period may reflect these changes, and a second stage regression involving vessel level social and demographic data could reveal covariates that deepen our understanding of the harvesting behaviour in the fishery. While, at the time of this study, the data required for this regression were not readily available, such an analysis might form a useful avenue for further research.

Chapter 5. Thesis Conclusion

The extent of the problem of excess capacity in world fisheries is still largely unknown, and capacity and capacity utilisation remain important topics for both theoretical and empirical investigation by fisheries economists. This thesis has contributed to this area of research through its investigation of the roles played by capital malleability and environmental variation in the development of excess capacity when race to fish and race to invest behaviours are prominent in the fishery, and has also investigated excess capacity when the race to fish exists in the case of a managed fishery.

The thesis has shown that malleability of capital is of central importance to the problem of excess capacity in fisheries where the race to fish and race to invest are prominent. The first essay shows that the range of steady state levels of excess capacity in such fisheries is directly linked to the gap between the purchase and resale prices of capital. The essay shows that there is less potential for excess capacity when these prices are close together, and it is less costly to dispose of fishing capital. Furthermore, when capital is non-malleable, the first essay reveals a potential trade-off between excess capacity and the biological condition of the fishery, suggesting that caution should be applied in the use of technical excess capacity as an indication of a fishery's health. Lastly, the essay demonstrates how higher initial levels of capital in the fishery will result in more overexploitation, a higher capital stock and less excess capacity in the steady state; and understanding this trade-off will help managers charged with managing fishing capacity. The second essay of this thesis has shown how the malleability of capital is an important determinant of the magnitude and persistence of excess capacity in race to fish and invest fisheries where environmental variation is important. In

contrast to the first essay, the second essay represents the malleability of capital by the rate of capital depreciation. When the capital is highly non-malleable, investments in capacity that are stimulated by periods of favourable environmental conditions remain in the fishery for long periods of time, creating a protracted level of excess capacity.

The role of environmental variation in the development of excess capacity is investigated in the second essay of the thesis. In general, this essay finds that the level of excess capacity that occurs in the fishery due to environmental variation is transitory, in that it is self-correcting over time. However, the significance of such excess capacity depends critically on the originating fluctuation in environmental conditions. In the case of positive fluctuations, the essay shows that there is an increase in fishing capacity as the fishers invest in additional capital to take advantage of better fishing conditions. When the increase in recruitment is transient, this extra capital leads to excess capacity when the fishing conditions return to 'normal'. When the increase in recruitment is permanent, i.e. for a positive regime shift, the extra capital continues to be fully utilised by the fishers and there is no excess capacity. The deterioration in fishing conditions in the case of negative regime shifts, or as a result of transient negative fluctuations, also generates excess capacity. In both cases, the drop in recruitment causes excess capacity the same as the return to 'normal' conditions in the case of transient positive fluctuations. For transient negative fluctuations, episodes of excess capacity conclude when the fishery's recruitment returns to 'normal', so that there is minimal change in the capital stock as a result of these fluctuations. In the case of negative regime shifts, however, the decrease in recruitment is permanent and the level of excess capacity dissipates away over time with the depreciation of capital, so that there is a permanent reduction in the capital stock. When there are regular cyclical fluctuations in recruitment, periodic improvements in the fishing conditions stimulate inefficient investment from myopic

fishers, which depreciate during the negative phase of the recruitment cycle. Simulations presented in the second essay demonstrate how this process can lead to a repeated cycle of excess capacity in the fishery.

The third essay of this thesis has investigated changes in excess capacity and efficiency over a time period that closely followed the introduction of an ITQ system in the Tasmanian rock lobster fishery; and also examined changes in those measures when the fishery entered a period of non-binding TAC from the 2008 to the 2010 quota years. It is commonly argued that by mitigating the race to fish the implementation of an ITQ system will reduce or eliminate excess capacity in the fishery. The results in the third essay of the thesis, however, find little evidence for such a change over the prolonged period of the Tasmanian rock lobster fishery that was examined. The analysis has demonstrated that the re-emergence of race behaviour in the fishery during a period of non-binding TAC was not associated with an increase in excess capacity. A reduction in technical efficiency was observed over this period to coincide with the re-entry of latent vessels, but no evidence was found for a decrease in unbiased capacity utilisation (i.e. an increase in excess capacity).

In conclusion, this thesis has particularly shown how the malleability of capital and fluctuations in the environmental conditions can contribute to the level of excess capacity, when the race to fish and race to invest are prominent. However, research in the thesis has a number of specific limitations, each of which suggests avenues for potentially fruitful further research. These limitations and avenues for further research are discussed in the following paragraphs.

Firstly, the malleability of capital is defined in terms of the rate of depreciation or by the difference between the purchase and resale prices of capital, as is common in the theoretical

literature. However, other economic factors might also play a role. For instance, inflexibility in the capital stock might arise due to an ageing workforce, where fishers' ability to retrain and transition to alternative occupations is limited. The malleability of capital might also increase by improving the liquidity of capital markets; reducing barriers to capital mobility, such as the transferability of fishing rights; or by facilitating the development of viable alternatives to fishing. However, any measure that improves the mobility of capital between fisheries would need to be balanced against creating the potential for (increased) spill-over of fishing effort. Given the importance of the malleability of capital for the problem of excess capacity, a further investigation of the factors that define such malleability forms an important area for further research.

Secondly, the models of the fishery in this thesis have adopted a representation of myopic behaviour known as projection bias. However, the role of expectations in determining fishers' behaviour is an understudied area, and a number of models of such behaviour have been developed in the theoretical literature, including myopic representations based on fishers' discount rate as well as models of perfect foresight. Further investigation into the nature of fishers' investment decisions would enhance our understanding of the processes leading to the development of excess capacity.

Finally, the thesis offers no way of distinguishing between wasteful excess capacity and economically efficient excess capacity. For example, under certain circumstances excess capacity can exist in the fishery to take advantage of fluctuations in environmental conditions. Fishers may maintain a buffer stock of capacity to increase harvesting during seasons where the recruitment of the fishery is higher than usual. Such behaviour was shown to be optimal in the case of the sole-owner fishery by Poudel et al. (2013), and while many empirical

studies (including the one presented in this thesis) quantify levels of capacity utilisation in world fisheries, the interpretation of these results is hindered by this potential for both wasteful and efficient forms of excess capacity. The measurement of excess capacity is therefore contextual to the structure and the effectiveness of fishing regulations, so that there is a need to exercise caution in the use of such measures as indicators of fishery performance. Some method for distinguishing wasteful and efficient component from empirical measures of excess capacity would be advantageous.

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